Chapter 7
Woody Biomass and Purpose-Grown Trees as Feedstocks for Renewable Energy

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7.1 The Forest Industry and Renewable Energy

The US government has committed to renewable energy and the recent American Recovery and Reinvestment Act of 2009 echoes the objectives of the 2007 Energy Independence and Security Act (EISA) and the Food, Conservation and Energy Act of 2008 (2008 Farm Bill). These bills have allocated more than US $16.8 billion in funding for renewable energy and energy efficiency projects over the next 10 years (ACORE 2009). Multiple Southeastern states have developed policy initiatives to encourage the development of the bioenergy industry, including consumption standards, tax incentives, subsidies and loans, as well as the identification of potential bioenergy crops including perennial grasses and trees.

Trees have been managed as a biomass crop for generations. Wood provides raw materials to a large wood products industry that includes sawmills, pulp and paper manufacturers, manufactured wood products facilities, and numerous niche applications. The US produces the largest amount of wood for industrial applications in the world, with the traditional forest products industry consuming approximately 600 million green short tons in 2006. In the Southeastern US, the total volume of hardwood and pine harvested annually is more than 365 million green short tons (RISI 2008). Much of this resource is renewed through re-planting, with approximately 950 million pine and 30 million hardwoods planted in the 2008/2009 planting year (McNabb and Enebak 2008). The majority of planted softwoods in the Southeastern US are *Pinus taeda* (loblolly pine) purpose grown on managed plantations, while the small number of planted hardwoods includes dozens of species intended primarily for non-industrial end uses such as recreation, conservation, restoration, reclamation and aesthetic values. Most harvested hardwoods for industrial uses come primarily from naturally regenerated stands.

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Wood production and wood harvests are dynamic in the US over time due to changing wood product demands and associated costs. The peak US roundwood harvest was in 1991 when industrial production was 18.8 billion cubic feet (ft^3 = 532.4 million m^3). Lumber and pulpwood-based products constitute the largest share (80%) of roundwood use. Since 1986, the harvest of wood for fuel and plywood has declined, with the largest increase in harvests directed toward pulpwood production (Howard 2005). However, the Southeastern US has increased timber production due to increased growth by non-industrial private landowners and fast growing pine tree plantations (Adams et al. 2006). Factors that are anticipated to affect the planting and harvest of trees in the future include emerging biopower and biofuels opportunities with new biopower and biofuel policies, loss of forest land to other uses such as development, and the emergence of carbon offset markets.

The use of trees for energy production is not new. Papermakers and lumber producers are the nation's largest renewable energy producers and consumers producing an estimated 28.5 million megawatts (MW) of electricity annually or enough to power approximately 2.7 million homes (AFPA 2009). The pulp and paper industry, as of 2005, contributed 1.22 quadrillion British thermal units (BTU) of energy to the nation's energy resources (one-fourth in the form of electricity and three-fourths in the form of useful thermal output), or slightly more than 1% of the nation's energy budget (Brown and Atamturk 2008). The industry itself provides for 60% of its own needs (Murray et al. 2006). This trend has been encouraged by rising energy prices for natural gas and petroleum, by environmental regulations, and by new and emerging technologies (Brown and Atamturk 2008). In the US in recent years, significant focus has been devoted to increasing energy independence and security, reducing dependence on non-renewable sources of energy, reducing our level of greenhouse gas emissions to mitigate climate change and fostering the development of rural economies. All of this has contributed to an increasing interest in the development of renewable energy technology from woody biomass.

Trees and wood were identified as part of the US bioenergy solution in the *Billion Ton Report* (Perlack et al. 2005). This report investigated the feasibility of producing the estimated 1 billion dry tons of biomass needed annually to meet the 30 x '30 goal of 30% replacement of the US petroleum consumption with biofuels by 2030. Two types for woody biomass were addressed: (1) wood residuals resulting from logging and mill/construction waste from the traditional forest products industry, and (2) wood produced specifically for energy as "perennial energy crops" that are grown more as an agricultural resource. Within the next 20 years, purpose-grown trees for energy are expected to account for 377 million dry short tons of the 1.37 billion dry ton total biomass resource potential at projected yields of 8 dry tons per acre per year (Perlack et al. 2005). The *Billion Ton Report* (Perlack et al. 2005) indicated that forest residues could supply approximately only 368 million dry tons biomass (Fig. 7.1).

There are multiple drivers for the use of trees for biopower and biofuels applications in the US. As mentioned earlier, there are substantial existing forest resources with an associated supply of unused or underused woody biomass that

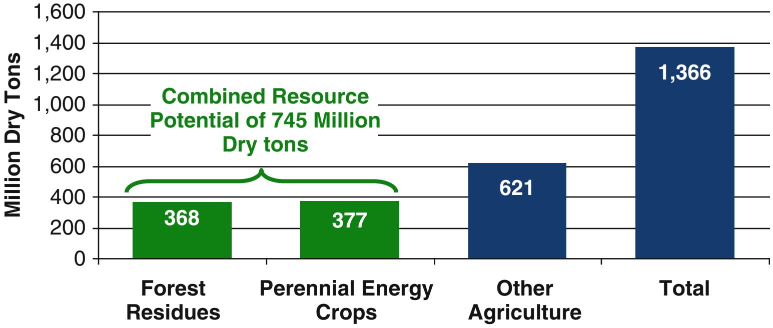

Fig. 7.1 Annual biomass resource potential (as million dry tons) in the US from wood and agricultural resources as presented in Perlack et al. (2005)

could be utilized for biopower and biofuels applications. Another driver for the utilization of woody biomass is the multiple energy applications associated with wood. Woody biomass, in particular wood waste, can generate power as a low cost boiler fuel, as a clean-coal alternative to coal fired utilities, as a source of gas that can be used in gas turbines to generate power, or as a substitute for natural gas used by certain industries. In addition, the technology to convert woody biomass cost-effectively into biofuels has been demonstrated on a pilot scale, with multiple commercial scale wood biomass biorefinery projects under way worldwide. Wood also can be converted into higher value fuels, such as clean diesel and jet fuel (Sklar 2009). Currently, the Southeastern US is a major supplier of renewable energy: its biodiesel plants produce 22% of the nation's biodiesel; its 12 operating ethanol plants produce 6.4% of the nation's ethanol; and its 534 biodiesel and E85 fueling stations represent 23% of the overall total (SAFER 2009). This presents an excellent opportunity for woody biomass utilization.

The Southern Alliance for Clean Energy (2009) estimates that biomass represents 60% of the near-term potential for expanding renewable energy. There has recently been a great deal of new development of cogeneration and wood pellet projects throughout the Southeastern US. The largest pellet mills ever built opened in this market during the past year and several additional projects have been announced. Wood demand from projects with announced start dates in the Southeastern US is expected to approach 50 million green tons by 2015 (Forisk Consulting 2009; L.M., unpublished results).

An independent study by the University of Tennessee estimates that the 25% replacement of petroleum-based fuel with renewable fuels by 2025 in the US equates to 86 billion gallons ethanol and 962 billion kWh energy by the year 2025 (English et al. 2006). Assuming trees represent 50% of the "energy crop" opportunity in the Southeastern US, this represents a total market of 258 million green short tons in the region by 2025. It is believed that wood residuals will be utilized first and that the expected woody biomass demand will quickly exceed residual supply (Fig. 7.2) (Abt et al. 2010). Multiple regional studies show dramatic increases in biomass prices with increasing demand when only forest residues wood are

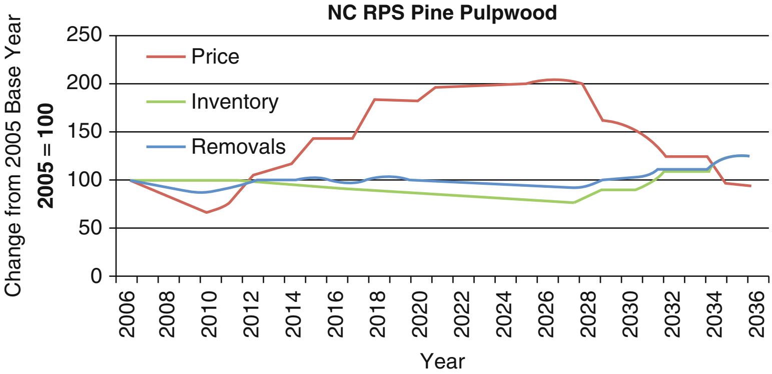

Fig. 7.2 Impact of North Carolina Renewable Energy Portfolio Standard on forest residual supply and price in the absence of purpose-grown energy crops (modified from Abt et al. 2010)

considered. It is therefore expected that future consumption will come from a mix of purpose-grown pine and hardwood trees. Using expected harvest yields and standard conversion rate assumptions this is the equivalent of 1,033 million and 574 million trees annually for pine and hardwoods, respectively. These numbers would more than double the current markets for woody biomass in the Southeastern US.

Woody biomass can provide renewable energy through two basic approaches: electricity generation through direct firing or co-firing of biomass with coal (biopower) and production of liquid fuels (biofuels). The technology and the fit of different species of woody biomass for these two renewable energy categories will be discussed in some detail in the following sections of this chapter. In addition, the improvements in tree genetics and silviculture that will be beneficial, improving the economic feasibility of woody feedstock for sustainable production of renewable energy will be addressed.

7.2 Biopower

The demand for renewable biopower is growing very quickly. Demand is influenced in large part by government mandates and incentives, and, to date, 28 states have implemented Renewable Portfolio Standard (RPS) legislation requiring that a portion of that state's electricity supply come from renewable sources (Pew Center on Global Climate Change 2008). This type of legislation has already been included in the American Clean Energy and Security (ACES) Act; H.R. 2454 was passed by the US House of Representatives in June 2009, and is currently being considered by the US Senate. The 25 x '25 alliance, comprised of a broad spectrum of participation from the agricultural and forestry sectors, has set a target of 962 billion kWh energy from biomass by 2025. Assuming trees represent 50% of the energy crop opportunity in the Southeastern United States, this represents a total market of 109 million green short tons by 2025.

The abundance of woody biomass resources in the Southeastern US have positioned this region to be a leader in bioenergy generation where 46% of the nation's biomass electricity was produced in 2007 (SAFER 2009). Wood and derived fuels are estimated to provide 184 trillion BTUs, with 50% of the feedstock coming from the Southeastern US (Energy Information Administration 2008). The vast majority of this can be attributed to the pulp and paper industry where by-products from production processes are routinely combusted to produce steam and electricity. The utilization of woody biomass for the production of electric power is already common but there is substantial potential for expansion. Biomass power plants exist outside of the pulp and paper industry that use forest-based biomass for power generation. In 2007, greater than 200 companies outside the wood products and food industries generated biomass power in the US to save fuel costs and earn emissions credits, particularly in regions where there is access to very low cost biomass supplies [US Department of Energy (DOE) 2007a].

Many coal-burning power plants in the US co-fire with wood, especially in the Southeastern US where highly productive forest plantations are prevalent. According to TimberMart (2009) a total of 32 biopower projects that would consume nearly 17 million green tons of woody biomass have been announced in the Southeastern US in the 21 months prior to the second quarter of 2009. For example, Southern Company has announced plans to convert six of its coal-fired power plants to co-fire with wood throughout the Southeastern US. Southern Company's Plant Mitchell and Southern Power's Nacogdoches Power Plant when combined are projected to consume more than 1 million green short tons of woody biomass annually (Forisk Consulting 2009). The wood consumption on an annual basis to generate biopower in the Southeastern US is projected to be nearly 28 million green short tons (Table 7.1).

7.2.1 *Processes for Energy Production from Woody Biomass*

The direct production of power from woody biomass involves the processes of co-firing and direct firing. Most of today's biomass power plants are direct-fired systems that are similar to most fossil fuel fired power plants (Bergman and Zerbe 2008).

7.2.1.1 Co-firing

Forest residues and low-value wood produced from traditional forest industries, agricultural crop residues, construction waste, municipal waste, storm debris, and dedicated energy crops, such as switchgrass, willow, and hybrid poplar, are typical biomass sources that can be used for simultaneous combustion with a base fuel such as coal to produce energy (typically electrical power). Wood can substitute for up to 20% of the coal in the boiler of coal-burning power plants. However power plants

Table 7.1 Wood biopower plants being established in the Southeastern US

Name	State	Electricity capacity (MW)	Start-up year	Estimated wood use (green tons)
Adage	FL	50	2012	500,000
Adage	FL	50	2012	500,000
Alabama Renewable Energy Alliance LLC	AL	13	2015	130,000
American Clean Energy	WV	28	2011	400,000
American Renewables LLC (Gainesville Renewable Energy Center)	FL	100	2013	1,000,000
American Renewables LLC (Hamilton County Renewable Energy Center)	FL	100	2013	1,000,000
Aspen Power	TX	50	2010	525,000
Bio-Gen	NC	6	2008	60,000
Bio-Gen	NC	4	2008	40,000
Bio-Gen	NC	2.5	2008	25,000
Bio-Gen	NC	5.3	2008	53,000
Biomass Gas & Electric	FL	75	2015	750,000
Biomass Gas & Electric	GA	30	2015	300,000
Biomass Gas & Electric – Northwest Florida Renewable Energy Center	FL	44	2011	410,625
Buckeye Cellulose – University of Florida	FL	12	2011	120,000
Coastal Carolina Clean Power	NC	25	2008	250,000
Decker Energy	NC	48	1990	550,000
Decker Energy	NC	50	2011	500,000
Decker Energy	TX	35–50	2014	500,000
Decker Energy (Fitzgerald Renewable Energy LLC)	GA	50	2011	600,000
Dominion Virginia City Hybrid Energy Center	VA	585	2012	585,000
Dominion/Pittsylvania Power Station	VA	80	2004	800,000
East Texas Electric Cooperative	TX	50	2014	500,000
Florida Biomass Energy (FB Energy)	FL	60	2012	600,000
Florida Crystals	FL	68	1995	900,000
Gainesville Regional Utilities/Gainesville Renewable Energy Center (GREC)	FL	100	2013	1,000,000
Global Energy Systems	GA	20	2013	200,000
Intrinergy – Coastal Paper	MS	30,000	2007	150,000
Milledgeville Central State Hospital	GA		1990	190,000
Multitrade Biomass Holdings	GA	18	2009	180,000
Novi Energy	VA	55	2012	1,000,000
NRG Energy	LA	1,730	2010	625,000
Oak Ridge National Laboratory/Nexterra Energy/Johnson Controls	TN		2011	70,000
Oglethorpe Power Corporation	GA	100	2014	1,000,000
Oglethorpe Power Corporation	GA	100	2015	16,000
Oglethorpe Power Corporation	GA	100	2015	32,000
Orangeburg County Biomass LLC	SC	35	2013	350,000
Peregrine Energy	SC	50	2012	200,000
Phoenix Renewable Energy	AR	20	2011	200,000
Plant Carl – Green Energy Partners, LLC	GA	25	2009	1,000,000
Pratt Industries	GA	9	2009	300,000

(*continued*)

Table 7.1 (continued)

Name	State	Electricity capacity (MW)	Start-up year	Estimated wood use (green tons)
Ridge Generating Station – Waste Management	FL	39.6	1994	500,000
Rollcast Energy	GA	50	2012	500,000
Rollcast Energy – Greenway Renewable Energy	GA	50	2010	400,000
Rollcast Energy – Loblolly Green Power	SC	50	2012	70,000
Rollcast Energy – Piedmont Green Power LLC	GA	50	2012	250,000
Savannah River Site D-Area/Ameresco	SC	20	2011	322,000
SI Group	FL	7	2006	27,000
Southern Company – Plant Mitchell	GA	96	2012	800,000
Southern Company – Plant Scholtz	FL	100	2013	1,000,000
Southern Company – Plant Sweatt	MS	80	2013	800,000
Southern Company (Nacogdoches Power)	TX	100	2012	700,000
Southern Company (Plant Gadsden)	AL	120	2013	1,200,000
SRS – A Area Steam Plant	SC		2008	450,000
SRS – K/L Area Heat	SC		2010	600,000
Sterling Planet at IP Riegelwood	NC	45	2013	450,000
SunMark Energy	TX	60	2012	2,500
Wiregrass Power LLC/Sterling Energy Assets	GA	40	2012	600,000
Yellow Pine Energy/Georgia Power	GA	110	2012	1,100,000
Electricity Total				27,883,125

Source: Wood Bioenergy South and ArborGen estimates

require some alterations in their process to utilize woody biomass, and this includes addressing the needs associated with woody biomass emissions procurement, handling and preprocessing (grinding to a fine size).

There are cost and environmental benefits to using woody biomass. It has been demonstrated that effective substitutions of biomass energy can make up 15% of the total energy input. Investments to modify coal-burning plants are expected to be US $100 to $700 per kW of bio-mass capacity, with the average ranging from $180 to $200 per kW. Co-firing results in a net reduction in emissions of sulfur dioxide (SO_2), nitrogen oxides (NO_x), and non-renewable carbon dioxide (CO_2); Bergman and Zerbe 2008). According to the National Renewable Energy Laboratory (1999), seven utilities burning at least 7% wood reduced their NOx emissions by 15% compared to burning 100% coal.

7.2.1.2 Direct Firing

In addition to the more common practice of co-firing, direct fire and gasification systems are also utilized. Most of today's biomass power plants that are direct-fired systems are similar to most fossil-fuel-fired power plants. In a direct-fired system, a large volume single-combustion chamber produces combustion gases that rise to the top of the boiler chamber to the heat exchange passages. Relative simplicity and low costs are features of direct-burn systems. Biomass power boilers are typically in the 20–50 MW range, compared with coal-fired plants in the 100–1,500 MW range (Bergman and Zerbe 2008). Use of wood pellets for direct fire energy production is becoming common in Europe in response to the European Union's ratification of the Kyoto Protocol (European Union 2002), and imported wood pellets from the Southeastern US are currently a primary source of woody biomass serving European markets. Several new pellet plants have been established to address this rapidly growing market (Table 7.2, Fig. 7.3).

Table 7.2 Wood pellet plants being established in the Southeastern US

Name	State	Pellet capacity (tons)	Start-up year	Estimated wood use (green tons)
American Green Holdings	GA	125,000	2010	300,000
Carolina Pacific Briquetting Co., LLC	SC	24,000 (2009) 300,000 (2010)	2009	600,000
Carolina Wood Pellets	NC	68,000	2009	136,000
FRAM / Appling County Pellets	GA	145,000	2007	140,000
Fulghum Fibers	GA	150000	2012	300,000
Green Circle Bio Energy	FL	500,000	2008	1,000,000
Green Circle Bio Energy	MS or GA	560,000	2011	1,250,000
Greenville Wood Products	FL	150,000	2009	300,000
Indeck Magnolia LLC	MS	90,000	2010	180,000
Integro EarthFuels (torrefied biomass)	NC	87,000 (2009), 350,000 (2012)	2009	700,000
Integro EarthFuels (torrefied biomass)	GA	168,000 (2012), 300,000 (2015)	2012	600,000
Lee Energy Solutions LLC	AL	75000	2010	150,000
Magnolia BioPower	GA	330,000 (2012), 660,000 (2015). 1,000,000 (2017)	2010	2,175,000
Nature's Earth Pellet	AL	90,000	1990	270,000
NexGen Biomass	AR	237,000 (2010), 395,000 (2011)	2010	790,000
Palmetto Renewable Energy	SC	16,000 (2008), 32,000 (2010)	2008	32,000
Phoenix Renewable Energy	AR	250,000	2011	500,000
Piney Woods Pellets	MS	50,000	2009	1,000,000
Point Bio Energy, LLC	LA	400,000	2010	540,000
Rockwood Pellets	GA	15,000	2006	500,000
Sparkman Wood Pellets	AR	18,000	1990	5,000
Woodfuels Virginia, LLC	VA	75,000	2008	300,000
Woodlands Alternative Fuels	GA	150,000 (2010), 300,000 (2011)	2011	600,000
Pellet Total				12,368,000

Source: Wood Bioenergy South and ArborGen estimates: Forisk Consulting 2009 and ArborGen estimates

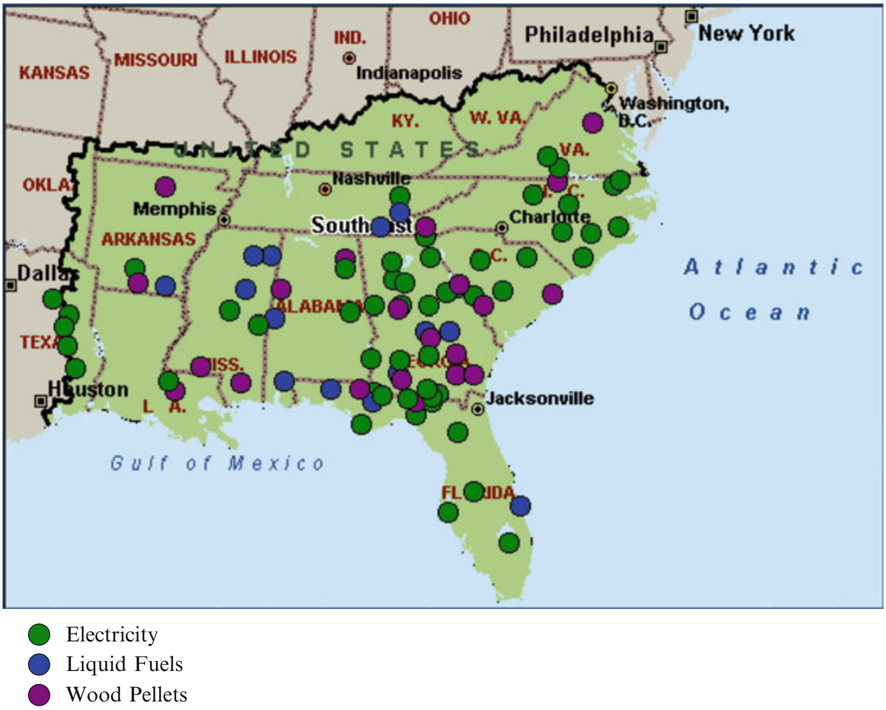

Fig. 7.3 Map of Woody Biomass Projects in the Southeastern US
Sources: Forisk Consulting 2009 & ArborGen unpublished data). Green dots Plants generating primarily electricity, blue dots plants generating liquid fuels, purple dots plants generating pellets to be used as solid fuel

7.2.1.3 Gasification

Wood gasifiers can be more efficient than direct burning, although the gas may require cleaning to remove undesired chemical compounds. New low-energy, gas-producing gasifiers with better cleaning and control systems are being developed. Air-blown circulating fluidized bed appliances utilizing woody biomass have provided hot-fuel gas for lime kilns and boilers since the 1980s. The size and moisture content of the feedstock can vary when used in this type of combustion bed. Circulating fluidized bed gasifiers are currently being implemented in coal- and natural gas-fired utility boilers, and for integration with gas turbines. In the integrated gas turbine system, heat is recovered from gas turbine exhaust (flue gas) and used to generate power and heat in a steam turbine. This combined-cycle technology has a positive environmental impact because more energy can be produced per pound of CO_2 emitted than in simple-cycle technology. Currently, it is expected that biomass gasification power plants will be relatively small (30–40 MW) due to the conversion efficiency of the technology and the amount of biomass and the land base required to support this type of facility (Bridgwater 2003).

7.2.2 Characteristics of Wood Feedstock that Impact Bioenergy Production

The physical and chemical properties of woody biomass affect its processing efficiency (depending on the specific process being used) as well as the logistical and cost parameters associated with delivered cost of the biomass and overall cost of energy production. The characteristics that contribute most significantly to the efficiency and costs of biopower generation are described below. These are characteristics that can be targets of genetic improvement for bioenergy applications.

7.2.2.1 Density

An important characteristic of biomass materials is their bulk density and/or volume after harvest and subsequent processing. The importance of the harvested bulk density is related to cost associated with transport. The energy produced per volume is an important economic parameter that impacts the cost of shipment, storage and use. Hardwoods have an average bulk density of 0.23 tons per cubic meter (t/m^3), while softwood has a bulk density of 0.19 t/m^3, which is higher than the average value for baled straw (Biomass Energy Foundation 2009). When energy content is expressed relative to volume, there can be significant variation reported in this energy content metric. This is due mainly to genotype *x* environment interactions that affect bulk densities as well as the impact of harvesting techniques on water content.

7.2.2.2 Energy Content

The mean energy content associated with biomass dry matter is a stable feature for a particular biomass type, and is relatively independent of external factors such as environment. Biofuels have a higher proportion of oxygen and hydrogen relative to carbon as compared to fossil fuels, and this reduces the energy value of the fuel as the higher energy is contained in the carbon–carbon bonds. Woody biomass energy yield is determined mainly by the contents of energy-rich compounds such as lignin, resin or cellulose, and bark generally has a 2% higher energy content than wood on a dry weight basis (Kauter et al. 2003). Fuel analysis for solid fuels, such as coal, measures chemical energy content stored in two forms: fixed carbon and volatiles. The calorific value (CV) or heat value is defined as the heat released during combustion per mass unit fuel. Wood has an average calorific value of 18.6 megajoules per kilogram (MJ/kg), which is slightly higher than that of straw (approximately 16–17 MJ/kg) and more than 50% less than that of coal (34 MJ/kg; Kauter et al. 2003). More detailed energy values for different types of wood can be found in Gaur and Reed (1998).

Depending on the energy conversion process selected, particular material properties become important during subsequent processing. Some constituents, such as moisture, ash, and alkali content, in woody biomass used for biopower can have a negative impact on the cost effectiveness of the process. The principal targets for biomass genetic improvements for bioenergy generation include intrinsic properties such as bulk density and chemical composition and biomass yield per harvest cycle.

7.2.2.3 Ash and Alkali Metal Content

The chemical breakdown of a biomass fuel, by either thermo-chemical or bio-chemical processes, produces a solid residue. When produced by combustion in air, this solid residue is called “ash” and forms a standard measurement parameter for solid and liquid fuels. The ash content of biomass affects both the handling and processing costs of the overall biomass energy conversion cost (McKendry 2002). In a thermochemical conversion process, ash chemical composition can be a significant factor in the combustion process because the alkali metal content [potassium (K), sodium (Na), calcium (Ca), magnesium (Mg) and silicon oxide (SiO_2) content] of biomass can react with any silica present in the ash to produce “slag”, which is a sticky, mobile liquid phase capable of blocking airways in the furnace and boiler. This can reduce plant efficiency and throughput, and result in increased operating costs. In addition, the chlorine (Cl) content of biomass contributes to corrosion and the silicate content can cause abrasion (Kauter et al. 2003). Silicate content can be a problem even if it is low in the intrinsic composition of the biomass. This is because, at harvest, contamination from soil can significantly increase the total silica content moisture content.

7.2.2.4 Moisture Content

Two forms of moisture content affect the thermochemical processing of woody biomass. Intrinsic moisture is the inherent moisture content of the material regardless of weather, and extrinsic moisture is the moisture content related to weather conditions during harvesting (McKendry 2002). Water content strongly influences the efficiency of energy production, as high water content reduces the net energy gain due to the thermal energy required for its vaporization.

An example of this is seen in poplar, a short rotation woody crop that is frequently used for the generation of biopower. The most problematic quality characteristic of this biomass is the elevated water content at harvest. The water content of poplar at harvest time typically varies between 54% and 61% of the fresh mass (Kauter et al. 2003). After felling, it changes depending on storage and processing. Agronomic approaches to control the drying process, such as leaving the felled biomass to dry prior to transport, are possible. The optimal moisture content for woody biomass transport and storage is 16% (Kauter et al 2003). The net

CV of wood with a water content of 16% is 15 MJ/kg (dry basis) while it is 6 MJ/kg (dry basis) for wood with a 60% moisture content.

One technology that can reduce the variability and negative consequences associated with moisture content is torrefaction. In torrefaction, green chipped wood waste is subjected to high temperatures under pressure, which drives off the moisture content and forms a high carbon content char. Torrefaction also produces gases from partial combustion and these gases can then be used to fuel the torrefaction process. The torrefied wood char is formed into torrefied pellets or briquettes that are low in sulfur. Torrefied wood has a BTU content that is slightly less than coal (Uslu et al. 2008) and can be substituted for coal in coal fired boilers without any boiler modifications required. Other advantages of torrefied pellets are that they do not collect moisture when stored and can be transported and stored at a lower cost than untorrefied wood. In the future, it may be possible for torrefied wood to be economically processed into a syngas that can then be liquefied into biofuel.

7.2.2.5 Yield

The quantity of woody biomass dry matter that can be harvested per unit land area determines the potential energy yield of the available land area. The biomass yield [dry metric tons (1,000 kg) of biomass per hectare or per acre (dmt/ha or dmt/ac)] combined with the high heating value (HHV) of the biomass determines the energy yield of a particular biomass crop. Experimental work on hybrid poplar species in the US Pacific Northwest, has produced yields of 43 dry metric tons per hectare per year (dmt ha^{-1} year^{-1}) compared to *Eucalyptus* yields in Brazil of 39 dmt ha^{-1} year^{-1} (Hislop and Hall 1996). Dedicated energy plantations to grow biomass will most likely address optimal yields as a function of species and available land. For example, a tree species that produces a high biomass yield, but requires intense management, will ideally be grown on good quality agricultural land to optimize productivity, while a tree species with a lower biomass yield but which is highly adaptive and does not require intense management will be grown on marginal land.

7.2.2.6 Energy Output

Energy output is the net energy balance for biomass after processing. For example, for every unit of fossil fuel energy used to grow, transport and convert willow biomass to electricity, 11–16 units of usable electrical energy are produced (Heller et al. 2003). At full generation rate, 1 kg woodchips converts to 1 kilowatt hours (kWh) via use in a gasifier/gas engine generator, giving an overall efficiency of conversion to electricity of about 20% without taking into account the potentially useful heat available from the gasifier/gas engine (Warren et al. 1995). The actual amount of energy recovered will vary with the conversion technology.

Independent of the process efficiency, the energy yield per hectare is affected by the biomass productivity of a specific energy crop. At yields of 15 dmt ha^{-1} $year^{-1}$, and with 1 dmt typically generating 1 megawatt hour (MWh), then 1 ha (based on a 3-year harvesting cycle) of short rotation woody biomass, such as poplar or willow, would provide 15 MWh/year (McKendry 2002). Therefore with the assumption of an annual operating time of 95%, a 1 MW gas engine/generator set would need approximately 550 ha to provide the necessary feedstock. This indicates that a significant amount of land (with the current productivity rates) is required to produce a relatively modest energy output of electricity due to the low efficiency of 20% in converting biomass into electricity.

However, combustion processes using high-efficiency, multi-pass, steam turbines to produce electricity can achieve an energy conversion efficiency of 35–40%, thereby reducing the required land to supply a 1 MW generator to between 270 and 310 ha (McKendry 2002). Integrated gasification combined cycle gas turbines can achieve energy conversion at about 60% efficiency, requiring approximately 110 ha to support feedstock production. However, the necessary land to grow a woody biomass crop to produce 1 MW is also dependent on the yield of that crop, indicating that efforts to increase yield through optimal genetics and silviculture is important.

7.2.3 Tree Species for Biopower

Many tree species already used for fiber and sawtimber applications are amenable to biopower and bioenergy production. Loblolly pine (Pinus taeda) and sweetgum (Liquidambar styraciflua) are highly adaptable trees commonly used in the Southeastern US for the production of pulp and paper, and are also potentially useful for bioenergy applications (Davis and Trettin 2006; Dickmann 2006), although their productivity per acre per year limits their potential to be used in short rotation energy plantations.

A sweetgum plantation grown for 7 years on old agricultural land has a productivity of only 1 oven-dry short ton per acre per year (odt ac^{-1} $year^{-1}$), although this productivity will increase with a longer rotation (Davis and Trettin 2006). Loblolly pine grown to a 20-year rotation can produce an average 4 odt ac^{-1} $year^{-1}$ (Mercker 2007). Hardwood species of Populus, Salix, and Eucalyptus are suitable for short rotation woody crops due to their higher productivity and their ability to readily regenerate from the stump after harvest. Currently 12,000 acres in the US are planted as intensively managed short rotation hardwoods.

Research has been conducted on growing short rotation trees for fiber, biopower, and biofuels in the US and other countries (Short Rotation Forestry Handbook 1995). The Biofuels Feedstock Development Program of the US DOE has funded research on improved clonal planting stock and associated silvicultural systems for short rotation woody crops (SRWC; Tuskan 1998) in order to achieve target productivity rates of 8 odt ac^{-1} $year^{-1}$ or greater (English et al. 2006).

Poplars and aspen (Populus sp. and their hybrids) as well as willows (Salix sp. and hybrids) are SRWC that can be successfully established in plantations. Populus is grown for bioenergy in Europe, the US Midwest and US Pacific Northwest. Salix is grown for energy in Europe, especially in England, and in the US Northeast. For example, short rotation willow crop yields range from 3 to 7 odt ac^{-1} $year^{-1}$ on 1–4 year rotations (Mead 2005). Populus deltoides (Eastern Cottonwood) planted on good sites can produce an average yield of 5 odt ac^{-1} $year^{-1}$ on 7–10 year rotations. For bioenergy applications the choice of species, the specific genotypes (clone or variety) and rotation length impact yield and quality. This is due to genotypic differences in growth pattern, nutrient use efficiency and relative proportions of different biomass fractions such as wood and bark.

Optimizing the management systems with respect to yield and fuel quality performance must be both genotype-and site-specific. Populus and Salix crops for bioenergy are typically managed as agriculture crops on arable soils. Short rotation coppicing, where new shoots and trees are regenerated from a cut stump, provides a cost effective option for increasing productivity per acre and decreasing feedstock costs. There is currently renewed interest in coppiced hardwoods for bioenergy and this is a subject of focused research (Andersson et al. 2002; Dickmann 2006).

7.2.3.1 Populus Species and Hybrids

Populus species fall into six morphologically and ecologically distinct sections, with the section *Aigeiros* containing cottonwood (*Populus deltoides* and *Populus nigra*), and the section *Populus*, which contains aspens (*Populus tremuloides*, *Populus tremula*, *Populus grandidentata*) and white poplars (*Populus alba*), representing the species most often used for bioenergy applications. However, the ease of hybridization allows for the development of many hybrids between these and other *Populus* species, such as *Populus maximowizcii*. Traditional breeding of poplars as single-trunk trees for wood production in short rotation forestry has been extremely successful. Hybrid poplars can be faster growing and more productive than parental species in short rotation silvicultural regimes. Sylleptic branching, in which lateral branches develop in the same year that their initial bud is formed, contribute positively to biomass in poplar by creating additional leaf area thereby increasing photosynthetic capacity and increasing volume (Ceulemans et al.1990; DeBell et al. 1996).

Poplars tend to be very site-sensitive and different genotypes may be limited to very specific sites in order to achieve adequate growth. Basic requirements for most *Populus* species are adequate water (minimum of 350 mm rainfall during the growing season) and nutrient supplies, deep soils and mild climatic conditions (average air temperature between June and September of at least 14°C). Biomass yield in poplar can be severely compromised when water is limited (Liang et al. 2006), and studies indicate that poplar tolerates water stress and low atmospheric moisture less than willow (Hinckley et al. 1994; Johnson et al. 2002). However, different poplar genotypes (clones) vary in their response to water stress indicating that genetic improvement for improved water stress response is possible (Karp and Shield 2008). In addition, for *Populus* to be grown as a SRWC, weed control is essential during plantation establishment (Kauter et al. 2003).

Aspen, unlike poplars and cottonwood, are more suited to poorer soils and can grow adequately in less favorable climatic conditions, such as those found in upland areas. Due to their slower typical growth rates, the silvicultural management system for aspen biomass involves longer rotations (approximately 10–12 years). These longer rotations enable aspen to attain mean annual growth increments of 10 dmt acre^{-1} year^{-1}as well as a higher proportion of high single shoot yields. Fuel quality improves with the single shoot mass due to an increased share of stem wood relative to bark (Kauter et al. 2003).

Two fundamentally different management systems are possible for SRWC. The traditional hybrid poplar system uses rotation cycles of 3–5 years, but this system is best for more fertile sites. As these fertile sites are also valuable for traditional agricultural use, the farmer may choose to harvest on longer rotation cycles of at least 7 years in order to achieve the yield and fuel quality to be economically competitive (Karp and Shield 2008). Poplars can be coppiced, initially producing many shoots that are subsequently thinned. However, in the 1st year after coppice, competition for light can result in very high shoot and stool mortality, so bioenergy poplars are often grown at densities of approximately 10,000 cuttings per hectare (Karp and Shield 2008). In comparative short rotation uncoppiced versus short rotation coppice trials, the coppiced systems yielded less, although coppicing enhanced intrinsic growth rates (Herve and Ceulemans 1996; Proe et al. 2002).

Biomass yields among poplars and aspen grown as SRWC differ considerably. Reported maximum yields can be 20–35 dmt ha^{-1} year^{-1} (Kauter et al. 2003). The highest yields were obtained from research trials with small plots that are actively managed and have significant edge effects while lower yields were reported for large demonstration plots. It is estimated that the average harvestable yields of poplars in the temperate regions of North America range between 10 and 12 dmt ha^{-1} year^{-1} (Kauter et al. 2003). This research has been validated by data presented in several reports. Poplar production in the US has been reported as ranging from approximately 8 t ha^{-1} year^{-1}) for cottonwood grown in flood plains on former agricultural land in Mississippi (Stanturf et al. 2003) to approximately 12 t ha^{-1} year^{-1} for hybrid poplar in the Southeastern US (de la Torre Ugarte et al. 2003) and approximately 13 t ha^{-1} year^{-1} for hybrid poplar in the Pacific Northwest (Stanton et al. 2002). These numbers reflect yields that are obtained reliably in large operational settings. To achieve biomass production at an overall rate of 11–12 t ha^{-1} year^{-1}, current poplar and aspen germplasm needs to be grown at 6- to 7-year rotations and 10- to 12-year rotations, respectively.

Increased silvicultural intensity (fertilization, irrigation, weed control) can improve yield, but at increased economic and energy costs. Breeding programs, such as described by GreenWood Resources (Stanton et al. 2002), can potentially increase yield by approximately 10% per rotation. In order to improve the sustainability and cost-effectiveness of *Populus* as a dedicated bioenergy crop, elite genotypes will need to be matched with the appropriate silvicultural management. For example, 20 Mt ha^{-1} year^{-1} yields of eastern cottonwood are possible on irrigated drylands in the Southeastern US. However, a yield improvement of 40% is considered necessary to achieve the desired cost-effectiveness, and this level of yield improvement will require genetic improvements and optimized silvicultural improvements (Gallagher et al. 2006).

The most problematic quality characteristic of *Populus* grown as a short rotation woody crop for biopower generation is its typically high water content (55–60%) at harvest time. This can be alleviated by storing unchipped material after felling on the field to lower moisture content.

7.2.3.2 Salix Species and Hybrids

Of the over 330 species of willows it is the shrub willows (*Salix viminalis* in Europe and *Salix eriocephala* in North America and Canada) that are most commonly used as bioenergy crops along with *S. dasyclados*, *S. schwerinii*, *S. triandra*, *S. caprea*, *S. daphnoides*, *S. purpurea*, and interspecific hybrids (Kuzovkina et al. 2008). Willow biomass plantations are easily and efficiently established from dormant stem cuttings using mechanical systems. The average planting density is 15,000–18,000 stools (individual plants or regenerating cut stumps) per hectare (Karp and Shield 2008). Coppicing is practiced routinely in willow SRWC production. Shrub willows respond to coppicing after the first growing season by prolific production of new stem growth in the second growing season. Coppiced willow is characterized by fast growth with many stems, followed by subsequent self-thinning. Above ground woody biomass is harvested during the dormant season on a 3- or 4-year rotation by a self-propelled forage harvester with a specialized cutter head, leaving the stool (remaining portion) behind. This cycle can be repeated for six to eight harvests before the stools need to be replaced (Karp and Shield 2008).

Genetic improvement in energy willow is focused on stem characteristics (height, diameter, straightness) and coppicing response (shoot number and vigor), as well as resistance to diseases, insects and frost damage (Karp and Shield 2008). However, different vegetative forms can achieve the desired biomass productivity. Some willows form a large number of thin stems (typically 11 per stool), relatively low leaf area index, and specific leaf area, while others produce fewer, larger-diameter stems (typically six per stool), and have a high leaf area index and specific leaf area. Both of these ideotypes can produce high yield (Tharakan et al. 2003). Willow genotypes that have early bud flush (even by a few days) may have a positive effect on total stem weight compared to genotypes with delayed growth cessation in the fall (Ronnberg-Wastljung and Gullberg 1999). Willow genotypes with higher water use efficiency and drought tolerance have been identified (Linderson et al. 2007). In the US, the most significant willow breeding and improvement program is based at The State University of New York College of Environmental Science and Forestry which conducts breeding and selection for high yielding clones that can sustainably produce high yields on a diversity of sites (Smart et al. 2005).

7.2.3.3 Eucalyptus

Eucalyptus is the most valuable and widely planted genus of hardwoods in the world and eucalypts demonstrate many agronomic traits, such as indeterminate shoot pattern, ability to coppice, resistance to drought, fire, and insects, and the ability to grow in acidic and low fertility soils, that enable them to be grown easily in large-scale plantings (Eldridge et al. 1994). In addition, many eucalypts display wood properties, such as high density, that make them very suitable for fuel and charcoal production, pulp and paper manufacturing, and sawn wood. In 2000, it was estimated that the area planted globally for Eucalyptus was 18 million ha in 90 countries (FAO 2000), with Brazil having the most intensively managed plantations with average productivities of 45–60m^3 ha^{-1} year^{-1} (Mora and Garcia 2000). *E. globulus* is the premier species for temperate zone plantations in Portugal, Spain, Chile and Australia. For pulp production and increasingly for solid wood, *E. grandis* and its hybrid with *E. urophylla* (*E. urograndis*) are grown in tropical and subtropical regions such as Brazil, South Africa, Congo, and China. The expansion of eucalypt plantations throughout the world can be attributed mostly to its superior fiber and pulping properties (Turnbull 1999). Genomics-aided improvement of Eucalyptus is underway (Grattapaglia 2004, Grattapaglia et al. 2004) and the Joint Genome Institute of the US DOE (2009) is nearing completion of the full genomic sequencing of *E. grandis*. It is anticipated that genetic improvement of Eucalyptus for industrial applications will increase dramatically after the publication of the Eucalyptus genome.

In the United States, some species of Eucalyptus are currently grown in Hawaii and warmer regions of California and Florida. In Florida, *E. grandis* operational plantings began in 1972 (Meskimen and Francis 1990). By the 1980s, it was planted on 5,650 ha (14,000 acres) in southwest Florida primarily as a source for landscape mulch. *E. grandis* grown in Florida has been tested successfully for pulpwood and fuel, and its wood has potential for poles, pallets, veneer, medium density fiberboard, and other products.

Eucalyptus is an ideal energy crop, with certain species and hybrids having excellent biomass productivity, relatively low lignin content, and a short rotation time. In Brazil, commonly planted Eucalyptushybrids such as *E. urograndis*, routinely yield 10–12 dry short tons acre^{-1} year^{-1}. Two Eucalyptus species, *E. grandis* and *E. amplifolia*, can be grown in Florida and are suitable for biofuel and biopower production. *E. grandis* grown in Florida has achieved a productivity exceeding 30 green short tons (approximately 15 dry short tons or 13.6 metric tons) acre^{-1} year^{-1}, with the potential to reach 55 green tons acre^{-1} year^{-1} (Stricker et al. 2000). This scale of productivity surpasses that seen with Populus and *Salix*, and addresses the biomass requirements for cost effective generation of biofuels and biopower from lignocellulosic feedstocks (Rockwood et al. 2008). In Florida, *Eucalyptus* utilization is likely to expand from the current mulchwood market to pulp and paper, biopower and biofuels (Rockwood et al. 2008).

7.2.4 Softwood Species for Bioenergy

Pinus taeda (Loblolly pine), also called Arkansas pine, North Carolina pine, and oldfield pine, is the most commercially important forest species in the Southeastern US. Loblolly pine plantations of the Southeastern US are prime candidates for the production of biomass for bioenergy because these plantations are already managed industrially to produce wood for pulp and paper production and for sawtimber. Loblolly pine occurs in subgenus *Pinus*, subsection *Australes* Loudon. This subsection is comprised largely of species found in the Southeastern US and the Caribbean, and most of the pines that co-occur naturally with this species in mixed stands (such as *P. echinata*, *P. elliottii*, *P. glabra*, *P. palustris*, and *P. serotina*) are in the same subsection (Kral 1993). The native range of loblolly pine extends through 14 States from southern New Jersey south to central Florida and west to eastern Texas, and it is the dominant tree on about 11.7 million ha (29 million acres) making up over one-half of the standing pine volume. It is a medium-lived tree with rapid juvenile growth. Loblolly pine is a highly adaptable species that responds well to silvicultural treatments and can be managed as either even-aged or uneven-aged natural stands, or can be regenerated artificially and managed in plantations.

Intensively managed pine plantations can be adapted easily to produce biomass for bioenergy applications. Loblolly pine biomass for bioenergy is currently being obtained from pre-commercial thinnings (see below) and from logging residues. As the pulpwood market in the US has decreased in recent years, there is a growing interest in providing wood to the energy industry. It will be possible for pine plantations to meet both the traditional forest industries and the bioenergy industry at the same time by using appropriate management practices. For example, agroforestry practices can be applied in plantation establishment in which double and triple rows of trees are planted, allowing some rows to be thinned at 12–15 years for bioenergy leaving the remaining trees to grow to a full 26-year sawtimber rotation (Foster and Mayfield 2007). It is anticipated that loblolly pine energy plantations will rapidly become a reality.

Yields of planted loblolly pine vary with plantation age, site quality, number of trees planted, and interactions of these variables. Yields generally increase with increasing age and site quality. Yields also increase with higher planting density or closer spacing; however, on some sites, moderately wide spacing of 2.4 x 2.4 m (8 x 8 feet) or 3.0 x 3.0 m (10 x 10 feet) can out-produce both wider and closer spacing. Mean annual increment in volume levels off at younger ages on better sites than on poorer ones. Better sites can carry more tree stocking densities than poor sites; consequently, initial spacing can be closer (Baker and Langdon 1990). Average total solid-wood yields of un-thinned loblolly pine planted at 1,730 seedlings/ha

(700/acre) on non-old-field sites at various locations within its range were predicted to increase from approximately 155 m^3/ha (2,200 cubic feet per acre) at age 15, to 300 m^3/ha (4,200 ft^3/acre) at age 30. Mean annual increment at age 30 was about 10 m^3/ha (145 ft^3/acre; Baker and Langdon 1990). Estimates are also available for a variety of site and stand conditions and geographic areas. If sawtimber is a primary management objective, wider tree spacing is used. However, thinning more densely planted stands can increase the diameter growth of the remaining trees, enabling multiple markets to be addressed where thinnings can be harvested at an intermediate time in the rotation for pulp or bioenergy with the full rotation trees being provided to the sawtimber market.

One current, but unfortunate, source of pine biomass for bioenergy applications are pine trees that have been killed by insect infestations in the western regions of North America, such as the mountain pine beetle infestations in Canada. It is estimated 10 million ha forest is already infected in Canada, potentially causing losses of up to 960 million m^3 wood. Bark beetles, such as the mountain pine beetle, are causing tree losses in the western areas of the US and Canada. Use of surplus wood from mountain pine beetle killed trees to generate power is being considered at several small size power plants (Kumar et al. 2008).

7.3 Liquid Biofuels

The established corn ethanol industry has laid the foundation for advanced biofuels in the US with ethanol facilities producing 9.2 billion gallons in 2008. Recent global food supply concerns as well as intrinsic limits to the sustainable production of corn have led to an increasing interest in the production of ethanol from non-food sources, including cellulose. The biofuels industry in the US is being driven in large part by government mandates for increased use of biofuels in the nation's transportation fuel supply. The Renewable Fuel Standard (RFS) included in the 2007 EISA mandates that 36 billion gallons of biofuels be included in the fuel supply by 2022 (US Environmental Protection Agency 2007).

7.3.1 Cellulosic Ethanol

Ethanol is the most common biofuel produced from wood, although wood can also be used to produce gasoline and diesel fuels. Ethanol is normally blended with gasoline to produce E10 (10% ethanol, 90% gasoline). In the US, the limitations on the blend ratios are currently driven by the automotive industry and the technologies used for automotive engines. In Brazil, E85 and E95 fuels are used and the "flex fuel" technology to allow the use of these fuels is readily available. The expansion of flex fuel vehicles (FFV) in the US will increase the consumption of ethanol by allowing the common use of fuels with higher ethanol contents. The domestic automobile manufacturers, seeing an opportunity to turn over the US fleet more rapidly, have committed to half of their vehicles sold being FFV by 2012 (Austin 2008).

The RFS mandates that 21 billion gallons of the 2022 biofuel supply will have to be "advanced biofuels" produced from non-corn feedstock (US Environmental Protection Agency 2008). Producing 21 billion gallons of cellulosic ethanol at a conversion rate of 100 gallons per dry short ton would require 210 million dry tons or roughly 420 million green tons if sourced entirely from woody biomass. Assuming trees represent 50% of the 'energy crop' opportunity in the Southeastern US, this equates to a total market of 150 million green tons by 2025 in the Southeastern US or 40% of current consumption for traditional forest products.

The US biofuel DOE has identified research to improve the cost-effectiveness of producing ethanol from lignocellulosic feedstock. Of significance is the US $375 million in funding the DOE has provided to three bioenergy research centers to develop advanced technologies to address current limitations in the production of bioethanol, including limitations that are related to feedstock inherent properties as well as productivity (US DOE 2007b). One of the centers, the BioEnergy Research Center led by Oak Ridge National Laboratory, is focusing its biomass improvement efforts on Populus in addition to switchgrass.

In the future, it is anticipated that ethanol production facilities will use forest-based biomass widely. Several commercial companies are developing pilot level or early commercial scale advanced biofuels production facilities using wood in the Southeastern US. According to *Wood Biomass South* published by Forisk Consulting (2009) and ArborGen unpublished data, cellulosic ethanol projects have been announced throughout the Southeastern US that would consume more than 9 million green short tons of biomass annually by 2015 (Table 7.3). For example, Range Fuels is constructing an ethanol plant in the state of Georgia that is expected to be operational in 2010. At this plant, wood waste is to be converted via a two-step, thermo-chemical conversion technology to a synthetic gas, to create power and ethanol using existing combined cycle generator technology.

Outside of the Southeastern US, another cellulosic ethanol plant, built by KL Process Design Group in Wyoming, became operational in 2008 and uses wood waste (KL Process Design Group 2008). The Flambeau River Biorefinery project will be the first modern US-based pulp mill biorefinery to produce cellulosic ethanol. It will be designed to produce 20 million gallons of cellulosic ethanol per year from spent pulping liquor. The new biorefinery, as designed, is expected to have a positive carbon impact of approximately 140,000 t/year. Project engineering has commenced with production of ethanol expected to begin as early as 2009 (PR Newswire 2009).

C2 Biofuels has a demonstration cellulosic ethanol plant that relies on Georgia pine trees as a feedstock and plans its first commercial plant in 2010. Their plant will use an enzyme-based system to convert the complex sugars in the wood chips into fermentable simple sugars. C2 Biofuels plans to have plants in various rural locations across Georgia, each capable of producing 50 million gallons ethanol a year (Center of Innovation for Agribusiness 2006).

Table 7.3 Woody biomass liquid fuel projects in the Southeastern US excludes mill residuals

Name	State	Liquid fuel capacity (mmgal)	Start-up year	Estimated wood use (green tons)
Bleckley County Biorefinery	GA	20	2015	200,000
BlueFire Ethanol	MS	18	2015	180,000
Buckeye Cellulose – University of Florida	FL	0.14	2010	13,800
C2 Biofuels	GA	55	2011	550,000
Cello Energy LLC	AL	20	2008	120,000
Enerkem	MS	10 (2013), 20 (2015)	2015	200,000
Gulf Coast Energy	AL	0.23 (2008), 10 (2013), 100 (2016)	2009	1,000,000
Gulf Coast Energy	FL	45 (2010), 80 (2013)	2010	800,000
Gulf Coast Energy	TN	10 (2014), 100 (2017)	2014	1,000,000
Jerome Bio-Refinery LLC	AR	110	2015	1,100,000
Liberty Industries Inc.	FL	7 (2011), 77 (2020)	2011	770,000
Mascoma Corp.	TN	5	2010	180,000
New Planet Energy (INEOS)	FL	8 (2010), 21 (2011), 100 (2013)	2010	1,000,000
Range Fuels	GA	10 (2010), 100 (2013)	2010	1,000,000
Raven Biofuels	MS	11 (2015), 33 (2018)	2015	1,157,625
Liquid Fuels Total				9,271,425

Source: Wood Bioenergy South and ArborGen estimates

7.3.2 Conversion Processes

7.3.2.1 Thermal Conversion

Fuel gas can be produced from biomass and related materials by either partial oxidation or by steam or pyrolytic gasification. The process of gasification involves heating biomass with about one-third of the oxygen necessary for complete combustion, producing a syngas composed of a mixture of carbon monoxide and carbon dioxide that may then be fed into a special kind of fermenter. Instead of sugar fermentation with yeast, this process uses a microorganism named *Clostridium ljungdahlii* (Gaddy 2000). This microorganism will ingest carbon monoxide, carbon dioxide and hydrogen and produce ethanol and water.

Alternatively, the synthesis gas from gasification may be fed to a catalytic reactor where the synthesis gas is used to produce ethanol and other higher alcohols through a thermochemical process. This process can also generate other types of liquid fuels. Currently, the most promising technology for processing woody biomass to biofuel is "two-stage thermal conversion" or "gasification with gas-to-liquids conversion" process. The gasification with gas-to-liquids conversion process converts all of the woody biomass to syngas, leaving no lignin components behind.

A major upside of biofuels produced by thermal conversion is the cogeneration of heat and power using diesel engine and gas turbine technology to generate ancillary revenue from the sale of excess steam, waste gases and heat that they produce (Sklar 2009). In some configurations, the excess steam and syngas is used to co-generate green power for sale to the grid. These second generation biorefineries can become much more economical than stand-alone biorefineries, if they are partially integrated into strategically located host facilities such as pulp and paper mills, and if they are able to realize a fair return on the steam, power and heat they provide these host plants.

7.3.2.2 Biochemical Conversion

Lignocellulosic biomass is a non-food, inexpensive and abundantly available source for fermentation into transportation fuels. Biochemical conversion of lignocellulose through saccharification and fermentation is a major pathway for liquid fuel production from biomass (Zhu et al. 2008). In this approach, biomass cellulose is converted to glucose using microbial or enzymatic actions. The glucose is then converted to alcohols through fermentation. Improved and novel methods are currently in development. It is anticipated that genomics-enabled ‘synthetic biology’ approaches will be key in developing efficient, inexpensive biofuel production systems (Rubin 2008).

Bio-based processes used to produce biofuels are currently relatively inefficient and expensive. Currently, bioconversion into ethanol has four unit operations: pre-treatment, saccharification, fermentation, and distillation. It is the pre-treatment and saccharification steps that most affect the economics of bioconversion. One of the major limitations is the accessibility of the cellulose in the plant cell wall to hydrolysis and saccharification agents due to the tight bonding of lignin to cellulose. Pre-treatment is a very critical step in the conversion of woody biomass into ethanol because its cost, efficiency and potential to produce compounds negatively influencing downstream processes can determine the economic feasibility of bioethanol production. The goal of the pre-treatment process is to remove lignin and hemicellulose, reduce the crystallinity of cellulose, and increase the porosity of the lignocellulosic materials.

After pre-treatment, cellulases are then able to saccharify or degrade the cellulose to glucose which in turn is converted to ethanol by yeast or bacteria during fermentation. Lack of low-cost and high-activity cellulose hydrolytic enzymes is currently an economic barrier to cellulosic ethanol production. When lignocellulosic raw materials are used in ethanol production, the main by-product is lignin, which can be used as an ash-free solid fuel for production of heat and/or electricity.

Limited progress has been made in improvements of woody feedstock pre-treatment, despite efforts made in the last several decades (Kumar et al. 2009). Dilute acid pre-treatment developed over a century ago is still the dominant process for biomass pre-treatment today (Zhu et al. 2008). The current available technology, which is based on dilute acid hydrolysis, has about 35% efficiency from biomass to ethanol. The overall efficiency, with electricity co-produced from the non-fermentable lignin, is about 60%.

It is estimated that current investment costs for a biorefinery are US $3,000 per KWh (at a nominal 2,000 dry metric tons per day input; Hamelinck et al. 2005). Improvements in pre-treatment and advances in biotechnology, especially through process combinations, have the potential to bring the ethanol generation efficiency to 48%. If the byproduct lignin is used for energy generation then the overall process efficiency is expected to be 68%. The combination of improved hydrolysis-fermentation efficiency, lower required capital investments, increased scale and cheaper biomass could bring the ethanol production costs from an anticipated US $31 per Gigajoule (GJ) ($0.65/l ethanol) in the next 5 years to $18 per GJ ($0.38/l ethanol) in 10–15 years (Hamelinck et al. 2005).

Pre-treatment

Pre-treatment must improve the formation of sugars or the sugar production via hydrolysis, avoid the degradation or loss of carbohydrate, avoid the formation of by-products inhibitory to hydrolysis and fermentation, and be cost-effective. Pre-treatment methods are varied and include physical (milling and grinding), physicochemical (steam pre-treatment/autohydrolysis, hydrothermolysis, and wet oxidation), chemical (alkali, dilute acid, oxidizing agents, and organic solvents), biological, or electrical (Kumar et al. 2009). The conditions employed in the chosen pre-treatment method will affect various substrate characteristics, which in turn govern the susceptibility of the substrate to hydrolysis and the subsequent fermentation of the released sugars.

For woody biomass, physical pre-treatment through size reduction is critical, regardless of whether other forms of pre-treatment are used. Reduction of wood to the level of fibers or fiber bundles is necessary to increase microbial or enzymatic reaction surfaces in the breakdown of cellulose (Kumar et al. 2009) and this process can be very energy intensive. First logs are reduced to chips then the chips are reduced to fibers approximately 2 mm long. This process is relatively energy intensive, taking up about 10–30% of the calculated wood ethanol energy available (Kumar et al. 2009). Chemical pre-treatment, prior to size reduction, can reduce the energy requirements of the size reduction step.

Steam explosion is the most common and cost-effective pre-treatment process for wood. In this method, biomass is treated with high-pressure saturated steam, followed by explosive decompression upon the sudden release of pressure. Steam explosion is typically conducted at a temperature of 160–260°C, with a corresponding pressure ranging from 0.69 to 4.83 MPa. The high temperature of this process causes hemicellulose degradation and lignin release. An enzymatic hydrolysis efficiency of 90% has been reported for poplar chips pre-treated by steam explosion (Grous et al. 1986). Steam pre-treatment with the addition of a catalyst is proving useful with a variety of lignocellulosic feedstock including wood (Kumar et al. 2009). The technology has been scaled-up and operated at the pilot-plant scale at the Iogen demonstration plant in Canada (Jorgensen et al. 2007). Although steam explosion is viewed as a relatively cost-effective pre-treatment process for hardwoods and agricultural residues, it is not equally effective for softwoods.

Ammonia fiber explosion (AFEX) is a physicochemical pre-treatment process in which lignocellulosic biomass is exposed to liquid ammonia at high temperature and pressure for a period of time followed by a sudden pressure reduction (similar to steam explosion). However, the AFEX process was not very effective for biomass with higher lignin content such as newspaper and aspen chips (25% lignin). Hydrolysis yields of AFEX-pre-treated newspaper and aspen chips were reported to be only 40% and below 50%, respectively (Kumar et al. 2009).

Dilute-acid pre-treatment is not highly effective on wood. Pre-treatment with 0.25–1.0% weight-to-volume hydrogen sulfate (H_2SO_4, sulfuric acid) of four timber species, aspen, balsam fir, basswood, and red maple resulted in hydrolysis yields that were high only for xylose (70% for balsam fir and up to 85% for aspen, with 90% for switchgrass) while very low yields were obtained for glucose for all species (approximately 11–14%). Balsam fir, unlike the other species, also had high yields for mannose (approximately 60%) due to its higher inherent mannan content (Yat et al. 2008).

Alkali pre-treatments, using sodium hydroxide (NaOH) or calcium hydroxide (CaOH) can be beneficial because they cause cell wall swelling, which increases exposed internal surface area while decreasing cellulose polymerization and crystallinity, breaking linkages between lignin and carbohydrates, and disrupting lignin (Kumar et al. 2009; Fan et al. 1982). However, alkali pre-treatments yield better results when lignin contents are 20%, which makes most wood less suitable than herbaceous feedstock due to its higher lignin content. Hardwoods respond better to this pre-treatment than do softwoods.

An organosolv pre-treatment method is being commercialized by Lignol Innovations (Bevill 2008). This process uses an ethanol-based organosolv step to separate lignin, hemicellulose, and extractives from the cellulosic fraction of woody biomass. The resultant cellulosic fraction is highly amenable to enzymatic hydrolysis and capable of generating glucose yields over 90% in 48 h or less (Pan et al. 2005). The liquor from the organosolv step can be processed readily to recover lignin, furfural, xylose, acetic acid, and a lipophilic extractives fraction. Revenues generated from the these byproducts, in addition to the ethanol produced from the glucose, generates sufficient revenue to enable cost-effective operations for even small facilities that process only 100 metric tons per day (Arato et al. 2005), which is a scale similar to a large sawmill.

Biochemical Process Commercial Status

To date, no large scale bioethanol plants that rely on woody biomass are operating in the Southeastern US. However, such a plant that utilizes urban wood waste operates in Japan (Green Car Congress 2009). A new plant, under construction by Verenium in Louisiana, will use primarily wood, including southern pine, as a source of biomass (Verenium 2009). Zeachem, Inc. uses a thermochemical and biological process hybrid process that has demonstrated, at laboratory scale, production rates of 135 gallons of ethanol per short ton biomass (Eggeman 2009). In 2008, Zeachem announced plans to build a 1.5 million gallon per year production plant in Oregon that will be sourced with poplar trees grown by GreenWood Resources, Inc. on intensively managed tree farms (Zeachem 2008).

7.3.3 Other Cellulosic Liquid Fuels

Although the bioethanol industry is growing rapidly, with ethanol production facilities and distribution centers increasing rapidly in number, ethanol as a transportation fuel has several disadvantages. Disadvantages of ethanol as a biofuel include its high solubility in water, which requires an energy-intensive distillation step; lower energy content relative to petroleum; its hygroscopic nature, which creates difficulties in pipeline distribution; and incompatibilities with many current vehicles at higher blending volumes. These disadvantages make other potential liquid fuels, such as methanol and butanol, worthy of consideration.

7.3.3.1 Methanol

Methanol is a one-carbon alcohol most frequently used in the production of formaldehyde, but it is also used in the production of biodiesel. In Europe, 10–20% of the weight of biodiesel can be methanol, while the remaining 90% is oil processed from agricultural crops (Kavalov and Peteves 2005). It also could become a useful transportation fuel on its own as methanol-powered fuel cells and fuel-cell/electric vehicles are developed. Methanol is also known as “wood alcohol”, as it was produced from wood in the early 1900s. With the development of a natural gas to methanol conversion process, the cost of producing methanol from wood was no longer cost competitive. However, technology exists today to produce methanol from wood, in a manner similar to methanol produced from natural gas, through gasification in which the syngas is converted methanol. Today, 1 short ton dry biomass can produce about 157 gallons methanol at a conversion efficiency of 50% (Vogt et al. 2009). This efficiency of conversion means that forest residuals and other wood sources now become an economically feasible feedstock.

7.3.3.2 Butanol

Butanol is a four-carbon alcohol commonly used in many industrial chemical manufacturing processes, although is can be used as a stand-alone transportation fuel or blended with gasoline or diesel. Its inherent chemical properties make it superior to ethanol for use in combustion engines due to its tolerance for water contamination and relatively low corrosive nature compared to ethanol (Vessia 2005), Each year 220 million gallons of butanol produced by petrochemical means are consumed in the United States (Young et al. 2007). Butanol can be produced from solventogenic bacteria, such as *Clostridium acetobutylicum*, which is used in the Acetone-Butanol-Ethanol (ABE) industrial fermentation process used widely in the early 1900s. This process utilizes a variety of feedstock, including ligncellulosic materials (Schuster 2000).

More advanced methods have made the process more cost-effective, and these are based on engineering microorganisms with butanol biosynthetic capabilities but also with increased tolerance to high levels of butanol thereby enabling greater butanol yields. For example, *Escherichia coli* has recently been engineered to produce isobutanol and other alcohols via a non-fermentative pathway that may be more readily adapted to large-scale production, using heterologous expression of *Lactococcus lactis* and *Bacillus subtilis* genes (Atsumi et al. 2007). Several companies are starting commercial-scale production of butanol with recently patented technologies. Gevo Inc. announced in 2009 the deployment of a 1 million gallon per year demonstration plant with engineered cellulosic yeast technology (Gevo 2009). ButylFuel, LLC, is developing a pilot fermentation plant in Ohio that uses patented technology demonstrated to produce butanol at a higher efficiency than the ABE process (Kiplinger Washington 2007). DuPont (E.I. du Pont de Nemours and Company) and British Petroleum Company plan to make biobutanol the first product of their joint effort, Butamax Advanced Biofuels, LLC, to develop, produce, and market advanced biofuels (Lane 2009). Their process also produces a recoverable amount of hydrogen, and other by-products such as acetic acid, lactic acid, propionic acid, acetone, isopropanol and ethanol.

7.3.4 Feedstock Characteristics Affecting Biofuel Production

Sections 7.2.3 and 7.2.4 describe characteristics of different tree species that can be used as energy crops. Features that affect delivered cost of the biomass to the processing plant are similarly important, whether or not the wood is undergoing a thermochemical or biochemical process, therefore many of the feedstock characteristics that affect yield and delivered cost are relevant for biofuel production. Wood chemical composition and moisture content have impacts that are specific for the particular process being used. In the biochemical processes, moisture content of the feedstock does not affect the energy required to generate liquid biofuels as it does in the thermochemical process.

Although both the biochemical and thermochemical processes are affected by wood chemical composition, the specific effects of chemical characteristics are not similar between the biochemical and thermochemical processes. Dry matter composition varies considerably among lignocellulosic energy crops affecting the ultimate yield and efficiencies in different bioconversion processes. Table 7.4 shows the percent dry weight of cellulose, hemicellulose, and lignin in softwoods and hardwoods as well for energy grasses. Since lignin is not easily biodegradable, the amount of lignin and the type of lignin can make a difference in the efficiency and costs of biochemical processing. In addition, the level of cellulose crystallinity affects the accessible cellulose surface area, and the type and amount of lignin and

Table 7.4 Consensus values for cell wall chemistry attributes as percentage of total dry weight of different energy crops. Values vary with site, season, cultivar and management. All values are percentages of mass at 100% dry matter

Feedstock	Lignin	Hemicellulose	Cellulose
Wheat straw[a]	15.1	24.6	33.2
Maize stover[a]	10.4	28	35
Switchgrass[a]	6.1	36	31.6
Miscanthus[a]	10.5	15.9	57.6
Willow[a]	19	14.0	55.9
Poplar[a]	20	23	40
Pine[b]	27–30	25–30	35–40
Eucalyptus[c]	34	13	38
Eucalyptus[d]	30	16	42

[a] Karp and Shield 2008

[b] McKendry 2002

[c] Rockwood et al. 2008, ArborGen unpublished data for 16

[d] *Eucalyptus urophylla* x *Eucalyptus urograndis* hybrid “EH”

hemicellulose can affect how cellulose is “protected” by lignin during the hydrolysis step. In the biochemical processes, the total amount of cellulose potentially affects the amount of glucose produced in hydrolysis and therefore ultimate biofuel yield, but this is dependent upon the pre-treatment method and the accessibility of cellulose to hydrolysis.

During hydrolysis of lignocellulosic materials a wide range of inhibitory compounds deleterious to fermenting microorganisms are formed or released. Hydrolysis procedures which involve treatment of lignocellulose at a high temperature under acidic conditions lead to the formation and liberation of a range of inhibitory compounds. These inhibitors are usually divided into three major groups: weak acids, furan derivatives, and phenolic compounds. These compounds limit efficient utilization of sugar hydrolysates during ethanol fermentation. Hardwoods and softwoods release different inhibitory compounds and this is somewhat dependent on the amount and types of lignin found in their wood. Hardwoods have syringyl and quaiacyl lignin while softwoods primarily have quaiacyl lignin. Hardwoods tend to have lower lignin levels than softwoods. For example, poplars contain much lower levels of fermentation-inhibiting extractives compared to softwood feedstock such as pine, thus the biochemical conversion efficiency of the biomass is correspondingly higher (Davis 2008; Palmqvist and Hahn-Hägerdal 2000). However, it is possible to generate ethanol through hydrolysis and fermentation of softwoods and it is projected that technology can be developed that will make the process cost-competitive with other feedstocks (Frederick et al. 2008).

7.4 Purpose-Grown Trees for Renewable Energy

Woody biomass from trees will compete with a variety of lignocellulosic energy crops, most of which are annually harvested (switchgrass, corn, sugarcane). Multiple approaches utilizing a variety of different energy crop species and production systems will be needed to meet the nation's renewable energy goals and it is clear that biomass from trees will play a significant role. The choice to use a specific energy crop must take into account regional conditions and needs, as well as logistical elements such as biomass transportation costs. Short rotation, purpose-grown trees, developed for high biomass productivity, have a variety of inherent logistical benefits and economic advantages relative to other lignocellulosic energy crops. It is expected that short rotation hardwood crops, such as fast growing species of Populus, Salix, and Eucalyptus and their respective hybrids, will be planted as purpose-grown wood on sites that enable high productivity and proximity to the processing plant, while existing pine plantations will be managed in a manner that enables harvests for energy end uses in addition to the traditional forest products industry.

In the Southeastern US, where the traditional forest products industry is an important economic driver, there already exists an established and accessible wood inventory and harvesting infrastructure. Current conventional forestry systems now provide biomass for energy applications as a by-product of timber production systems. Any harvesting operation, whether thinning in young stands, or cutting in older stands for timber or pulpwood, can yield tops and branches usable for bioenergy. Stands damaged by disease or fire are also sources of biomass. Forest residues can represent 25–45% of the total biomass at the time of harvest, and utilization of these residues can provide additional revenue from a stand while reducing the risks of possible forest fires, pests and disease.

It is anticipated that, in the future, forestry systems may also produce biomass for energy as a primary product. However, landowners who grow woody biomass have the advantage of having multiple markets for their wood, such as sawtimber and pulp and paper, in addition to biopower and biofuels. This provides the landowner an economic hedge when the market demands for a particular end-use might be lower than expected. The grower is provided a choice in harvest time and multiple end uses such as traditional forest products and energy products such as cellulosic ethanol and power generation through direct firing, co-firing, or wood pellet systems. The stand uniformity and improved genetics of plantations of purpose-grown trees, as compared to naturally regenerated forests, enables overall higher yields and improved management and harvesting efficiencies.

Trees have a variety of inherent logistical benefits and economic advantages relative to other biomass production systems. Many of these advantages are driven by the fact that trees can typically be harvested year-round, and provide a living inventory of available biomass as the trees continue to grow (Sims and Venturi 2004). The multi-year harvest cycle of trees serves to mitigate the risk of annual yield fluctuations experienced by other crops due to the acute effects drought, disease, pests and abiotic stresses. Multi-year harvest rotations also allow the biomass to be harvested in response to market demand, as well as provide a processor with multiple years to secure the acres needed to supply a given quantity of biomass, which improves deployment feasibility. Trees, in general, compare favorably with respect to storage-related costs, as annual herbaceous species typically must be harvested within a defined window of time and processed immediately to reduce the risk of decay in storage. In contrast, trees are stored essentially in the field. Wood can be stored easily dried at the roadside, at a distribution center, or at a conversion facility, and distributed during peak demand periods. Processors utilizing annually harvested feedstock must either secure more feedstock than is needed or run the risk of having to shut down the facility during a bad year. The standing inventory and ease of storage helps the processor avoid this by smoothing natural yield fluctuations allowing for supply to be more easily matched with demand.

The higher density of wood relative to cereals or grasses increases the cost-effectiveness of transport from the field to the processor, especially for logs. Transport costs are largely a function of the distance traveled and the energy density, e.g., energy content per unit volume (frequently measured as Megajoules per cubic meter, MJ/m^3), of the biomass being transported, and road transport accounts for about 70% of the total delivered biomass fuel cost (Transport Studies Group 1996). Forest residues normally have much lower densities and fuel values than logs, and transport cost effectiveness can be enhanced by increasing density close to the harvest site. This is done by size reduction via grinding or chipping, or by compaction into “compact residue logs” that can be handled efficiently (IEA BioEnergy 2002).

The multi-year harvest cycle for trees also provides some environmental advantages compared to crops that are harvested annually. For example, soil cultivation in a poplar energy plantation is only required twice for a 6- to 8-year harvest rotation, which reduces soil erosion associated with annual cultivation. While biomass yields and total land footprint to feed a processing plant may be similar between trees and annually harvested crops, trees only require that a fraction of the total land footprint would be planted or harvested in any given year (Table 7.5). This has a positive impact on the energy costs and CO_2 inputs required to supply an energy feedstock. Trees provide the added benefit of mitigating climate change through the sequestration of atmospheric carbon.

Many tree species already used for fiber and sawtimber applications are amenable to biopower and bioenergy production. Loblolly pine (*Pinus taeda*) and sweetgum (*Liquidambar styraciflua*) are species commonly used for pulp and paper production in the Southeastern US, but their typical productivity and rotation age limits their potential for use as SRWC energy crops (Davis and Trettin 2006; Dickmann 2006), although these species, especially pine, will definitely have use

Table 7.5 Total and annual acreage needs for trees relative to annually-harvested energy crops, data (generated from an ArborGen financial model by L. Mullinax)

Feedstock	Biomass needed (MM green tons/year)	Productivity (green tons $acre^{-1}$ $year^{-1}$)	Rotation length (years)	Total acres needed (MM)	Acres planted annually (MM)
Trees	100	20	6	5	0.83
Annually harvested crop	100	20	1	5	5

as bioenergy feedstock through increased biomass yields per acre via altered management regimes such as increased planting density. Research has been conducted on growing short rotation trees for fiber, biopower, and biofuels in the US and other countries (Short Rotation Forestry Handbook 1995). Attempts at shorter rotation sweetgum (7-year-rotation on old agricultural land) produced only 1 odt acre^{-1} year^{-1} (Davis and Trettin 2006), and shorter rotation loblolly pine (20 year rotation on nonagricultural land) produced an average 4 dry tons acre^{-1} year^{-1} (Mercker 2007). The Biofuels Feedstock Development Program of the US DOE set their target productivity for short rotation woody crops as 8–10 odt acre^{-1} year^{-1} and have invested in developing improved clonal planting stock and associated silvicultural systems to achieve this productivity level (Tuskan 1998; English et al. 2006). Populus and Salix species are hardwoods that currently can be managed intensively in plantations, but these trees still fall short of achieving the desired productivity levels. Short rotation willow crop yields range from 3 to 7 dry short tons acre^{-1} year^{-1} (Mead 2005). *Populus deltoides* (Eastern Cottonwood) planted on good sites can produce an average yield of approximately 5 odt acre^{-1} year^{-1}.

Currently, the two main silvicultural systems for biomass hardwoods utilize the establishment of moderately dense stands of cottonwood (*Populus deltoides*) with 7- to10-year rotations, or the establishment of stands of willow (*Salix* species) harvested as a coppice on a 1- to 4-year rotation. Short rotation coppicing of hardwoods offers the promise to produce biomass for bioenergy. Coppicing is the process by which new shoots and trees are regenerated from a cut stump following harvest. The use of coppiced hardwoods for this purpose is not novel although it is the subject of renewed interest and focused research (Andersson et al. 2002; Dickmann 2006).

Tree genetic and silvicultural research is underway to provide the optimal productivity gains required for tree biofuel and biopower applications. Productivity improvements, such as those provided through advanced planting stock, optimal siliviculture, and biotech traits, will be important for the cost effective deployment of short rotation trees for biomass applications. The economics of a purpose-grown tree feedstock for energy may not be feasible without significant genetic improvement in the base growth rate. Other useful trait improvements will be dependent on the inherent biological and genetic limitations of the utilized genotype and its ability to respond to varying climate, soil and moisture conditions.

7.4.1 Genetic Improvement for Productivity

Domestication, breeding and selection of forest tree species has resulted in direct and indirect changes in the genetic make up of trees grown for industrial applications. Forest tree domestication was accelerated during the latter half of the twentieth century, with conventional breeding methods applied to forest tree populations to improve growth, volume and wood quality traits (Burdon and Libby 2006). The application of biotechnology to forest tree species is expected to further accelerate such improvement (Sedjo 2001), including new developments for bioenergy applications. Commercialization of improved planting stocks, based on new varieties generated through clonal propagation and advanced breeding programs, as well as further improvements with biotechnology with high value traits, will occur in the near future. These trees will further enhance the quality and productivity of plantation forests (Nehra et al. 2005) and will provide a renewable resource for industrial applications.

There are two major approaches to achieve dramatic productivity improvements in purpose-grown plantation trees. The first is to use genes to genetically improve the productivity of native trees, such as Populus species and pine. The second strategy is to genetically improve the adaptability of exceptionally productive non-native trees, such as eucalypts, to enable their operational use in the Southeastern US.

7.4.1.1 Native Tree Species—Populus

Various native Populus species and their hybrids (with native and introduced species) are among the most rapidly growing trees adapted to temperate climates. However, the high inherent growth potential of trees in this genus is often manifested only at the most favorable sites. *Populus* genotypes typically respond optimally to specific sites and cannot be grown across diverse sites. A research objective is to develop *Populus* genotypes that can demonstrate wide adaptability across a range of sites and environmental conditions. Unless strategies to increase productivity are employed together with tolerance to abiotic and biotic stresses, plantations of *Populus* species and hybrids will remain limited.

Several different strategies offer the potential to overcome these limitations and allow *Populus* to play an increasingly important role in bioenergy initiatives. The first and most straightforward of these strategies is through traditional breeding to generate hybrids and varieties that grow fast, have high volume increments, and can grow across a wide range of sites. For example, advanced Populus clones have been developed by companies such as MeadWestvaco (Robinson et al. 2006) and International Paper, with continued development through ArborGen, LLC, and GreenWood Resources, Inc., to have greater productivity and adaptability. These programs typically consist of breeding among selected genotypes within a species, or between species, and testing the seedling progeny in a series of field trials. The first tests are in a nursery at close spacing to evaluate the genotypes for broad adaptability and resistance to various pests, which are then followed by one or more series of vegetatively propagated field trials in which the varieties are further screened for suitability to diverse planting sites. Commercial candidates are typically selected based on projected yields and wood properties after as many as 10 years of field testing.

Genomic-aided improvement is now possible in *Populus* species. *Populus trichocarpa* was the first tree to have its genome sequenced, and genes related to traits that contribute to maximizing biomass yield per unit land area will be investigated

(Tuskan et al. 2006). The US DOE has described the optimal bioenergy tree attained through accelerated domestication enabled by genomics-aided breeding: short stature to increase light access and enable dense growth, large stem diameter, and reduced branch count to maximize energy density for transport and processing, harvest time of only a few years, and modification of the macromolecules that comprise the cell (Ragauskas et al. 2006; Tuskan 2007). Using a gene homology approach, in conjunction with gene function and expression analysis, candidate domestication genes for these traits have been identified. These include many genes involved in cellulose and hemicellulose synthesis as well as those believed to influence various morphological growth characteristics such as height, branch number and stem thickness (Kalluri et al. 2007; Busov et al. 2008; Ragauskas et al. 2006). In addition, the Oak Ridge National Laboratory, in conjunction with the Bioenergy Feedstock Development Program and Boise Cascade Corp., is developing methods to identify drought-tolerant genotypes based on the presence of certain leaf metabolites (Oak Ridge National Laboratory 2009). Functional validation of candidate genes will occur through high-throughput production and phenotypic analysis of transgenic *Populus* in which these candidate genes are up- or down-regulated.

Populus improvement via transgene insertion is a second viable approach to achieve productivity improvements. Introduced agronomic traits, such as herbicide tolerance and insect resistance, can result in significant biomass yield benefits (Meilan et al. 2000). Weeds have been shown to have a major negative impact on the growth and establishment of *Populus* grown as SRWC, with survival and height growth being significantly improved with the use of herbicide treatments (Hansen et al. 1984; Schuette 2000). Transgenic *Populus* resistant to glyphosate have demonstrated the ability to effectively control weeds by an over-the-top spray regime (Meilan et al. 2000; James et al. 2002; Donahue et al. 1994) and to potentially reduce the costs associated with alternative methods such as cultivation or directed herbicide spray to control weeds. *Populus* has been transformed with modified *Bacillus thuringiensis* (Bt) endotoxin genes that conferred resistance to lepidopteran pests, such as gypsy moth (*Lymantria dispar*), the forest tent caterpillar (*Malacosoma disstria*) and the chocolate tip moth (*Clostera anachoreta*; McCown *et al.* 1991; Robison et al. 1994; Wang et al. 1996) as well as to coleopteran insects such as the cottonwood leaf beetle (*Chrysomela scripta*; Meilan et al. 2000). The cottonwood leaf beetle resistant transgenic trees (Meilan et al. 2000) and chocolate tip moth (chocolate tip moth; Ewald et al. 2006) demonstrated reduced defoliation and increased growth in field trials in the US and China, respectively.

Another approach to increase total biomass production in trees is to improve the ability of trees to thrive at less than optimal nitrogen levels. For example, glutamine synthetase (GS) is responsible for ammonium assimilation by producing the amino acid glutamine from glutamic acid (Good et al. 2004). Kirby and co-workers at Rutgers University, who studied over-expression of a conifer cytosolic glutamine synthetase (GS1) in *Populus* (Fu et al. 2003; Man et al. 2005), showed that greenhouse-grown GS1 transgenic trees had a greater than 100% increase in leaf biomass relative to controls when grown under low nitrogen conditions (Man et al. 2005). The effect was less marked when more nitrogen was available to the trees.

Transgenic *Populus* characterized by over-expression of a pine cytosolic GS gene exhibits other beneficial phenotypes including enhanced tolerance to water stress (El-Khatib et al. 2004), and enhanced nitrogen use efficiency (Man et al. 2005). One other gene involved in nitrogen utilization is glutamate synthase (GOGAT), which is involved in recycling of ammonium ions in plant tissues. When NADH-GOGAT, found predominantly in non-photosynthetic cells, was overexpressed in tobacco, a 30% increase in foliar biomass was achieved although the nitrogen-to-carbon ratio remained unchanged (Chichkova et al. 2001).

Suboptimal nutrient and water availability limit *Populus* productivity on many sites. Genes and gene families have been identified that have the ability to alter plant responses to water and nutrient limitations (Tuskan et al. 2006). Introduced genes being tested in Populus include the *Populus tremula* and *Arabidopsis* stable protein 1 (SP-1) gene, as well as genes involved in metabolic processes responsive to drought, such as redox proteins, transporter proteins, signal transduction proteins and transcription factors (Polle et al. 2006). Drought and salt tolerance was observed in transgenic *Populus tomentosa* transformed with a constitutively expressed *Arabidopsis thaliana* phospholipase Dα (AtPLDα) gene and the level of tolerance was correlated to the level of expression of the introduced gene (Zhang et al. 2008). Various forms of phospholipase D have been implicated in signal transduction, membrane trafficking, and membrane degradation. Over-expression of At*PLDα* affected stomatal closure and plant water status via increased sensitivity to abscisic acid (Sang et al. 2001). General stress tolerance genes might also have a positive impact on productivity. It is also possible that genes that confer stress tolerance or delay senescence could also improve growth under environmental stress conditions or could extend the growing season, and it has been shown that suppression of a gene, deoxyhypusine synthase (DHS), which is part of the stress response pathway, increases vegetative and reproductive growth in the model plant *Arabidopsis* (Duguay et al. 2007).

Tree growth is also affected by genes involved in cell, tissue and organ development. An introduced β-1,4-endoglucanase (cel1) involved in cell wall synthesis during cell growth improved growth in transgenic Populus (Shani et al. 2004). Genes involved in leaf size and structure, stem development, timing of bud flush, and leaf senescence all may influence biomass accumulation, rotation time, and growth rate. For example, it has been shown that a gibberellin catabolism gene, GA 2-oxidase, can affect tree height (Busov et al. 2003). Over-expression of a Populus FT (flowering time) gene enabled transgenic *Populus* to continue growing despite exposure to short days that stimulate dormancy (Böhlenius 2006). This strategy could possibly be used to delay dormancy and extend the growing season by several days and enhance biomass yields over a multi-year rotation.

7.4.1.2 Native Tree Species—Pinus

Loblolly pine, unlike many Populus species, has the advantage of being widely adaptive across many sites in the Southeastern US below 2,000 feet in elevation.

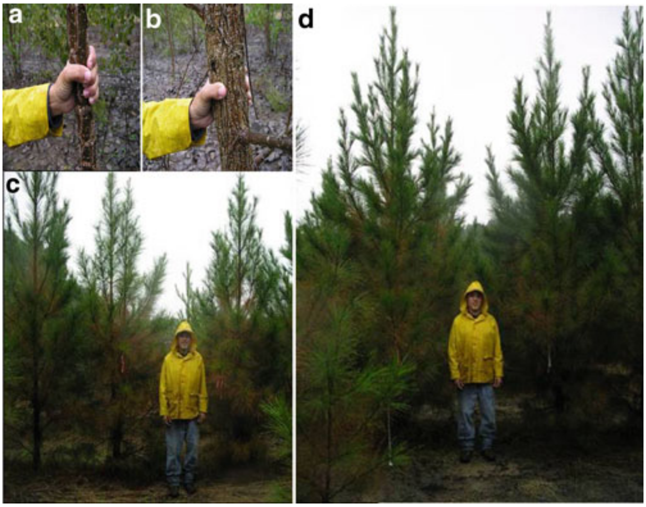

Fig. 7.4 Three-year-old field trials of transgenic trees. **a** Control transgenic cottonwood (Populus deltoides) expressing the β-glucuronidase gene (GUS). **b** Transgenic cottonwood with ArborGen proprietary growth gene; **c** Control transgenic loblolly pine (Populus taeda) with GUS gene; **d** Transgenic loblolly pine with the same ArborGen proprietary growth gene as in **b**

However, loblolly pine's long rotation time (15 years for pulp wood applications and 23 years for sawtimber applications) is an economic limitation for its use in biofuel and biopower applications. To address this limitation, ArborGen, LLC, and other tree breeding organizations, are employing advanced breeding and crossing methods to develop high-performing traditional seedlings that have improved growth, disease resistance and form. ArborGen and two other tree improvement companies (CellFor, Inc. and Weyerhaeuser Co.) have utilized a tissue culture process called somatic embryogenesis to mass propagate selected elite loblolly genotypes (Grossnickle and Pait 2008). Improvements in traditional breeding and selection are predicted incremental to achieve 35% volume gains and sawtimber rotation times of approximately 20 years. Biotech gene insertion methods will be necessary to develop loblolly pine with the productivity levels required to enable the production of high value sawtimber in shorter rotation cycles. Early research results indicate that rotation times of 15 years may be possible. ArborGen has introduced candidate genes associated with improved growth into loblolly pine, and obtained results that indicate that 3-year-old transgenic trees in field trials can demonstrate nearly double the i biomass production relative to control trees (Fig. 7.4). Transgenic pine with reduced and altered lignin have also been produced (M.A.H., unpublished results).

7.4.1.3 Introduced Tree Species—Eucalyptus

The use of introduced trees is not new to forestry, with many of planted Populus trees in the US being hybrids with species brought to the US from Europe and Asia

(Stanton. 2003). Eucalyptus is not native to the US, but it is is grown widely for industrial forestry globally because of its good wood fiber properties, high pulp yields, excellent biomass productivity and ability to grow on upland sites. *Eucalyptus grandis* and its hybrids have the greatest biomass yield potential and are commonly used in the Brazilian pulp and paper industry. The positive attributes of Eucalyptus make it attractive for commercial use in the Southeastern US. However, Brazilian elite operational genotypes (or clonal varieties) are typically adapted to tropical climates and are sensitive to freezing temperatures. Efforts to introduce Eucalyptus to the Southeastern US began in 1971 as part of the North Carolina State University Hardwood Cooperative research program (Jahromi 1982). Later the International Paper Company in Bainbridge, Georgia conducted the first *Eucalyptus* screening trial in 1972 using *Eucalyptus viminalis*, a species with natural frost tolerance (Jahromi 1982). However, even these more tolerant trees demonstrated dieback and reduced height growth by the extreme fluctuations in temperatures in the Southeastern United States where temperatures can go from 21°C during the day to –1°C at night (Meskimen et al. 1987). Unfortunately, the species that survived the best in cold temperatures did not have the desired productivity.

This situation is changing. It is now possible to plant highly productive genotypes of Eucalyptus that have been modified via biotechnology to tolerate the freezing winter conditions in the Southeastern US. This advance was made possible by the discovery of the C-repeat/dehydration-responsive element binding (CBF/DREB) factor cold-response pathway (Jaglo-Ottosen et al. 1998; Liu et al. 1998). Over-expression of CBF genes conferred freezing tolerance, drought tolerance, as well as salt tolerance in *Arabidopsis* (Liu et al. 1998; Kasuga et al. 1999). Similarly, over-expression of *Arabidopsis* CBF genes in *Brassica napus*, *Nicotiana tabacum*, and *Populus* induced the expression of CBF-targeted genes and increased freezing and drought tolerance of transgenic plants (Jaglo-Ottosen et al. 2001; Kasuga et al. 2004; Benedict et al. 2006). Genes homologous to the *Arabidopsis* CBF genes have been demonstrated to be effective in inducing freeze tolerance. Over-expression of a pepper CBF homolog (CaPF1) in tobacco and *Arabidopsis* improved their freeze hardiness (Yi et al. 2004). The maize CBF homolog, ZmDREB1A, improved freezing and drought tolerance in *Arabidopsis* (Qin et al. 2004). However, not all CBF homologs are equally effective, differing in the interaction of the specific CBF homolog with the species in which it is being expressed.

Heterologous expression of the *Arabidopsis* CBF1 resulted in enhanced chilling tolerance but not freezing tolerance in transgenic tomato (Hsieh et al. 2002; Zhang et al. 2004). In rice, four CBF homologs have been identified, and over-expression of one of the homologs (OsDREB1A) in *Arabidopsis* conferred enhanced freezing tolerance and high-salinity tolerance (Dubouzet et al. 2003; Ito et al. 2006). One undesirable phenotype associated with strong constitutive over-expression of CBF genes is dwarfing (Zhang et al. 2004). To overcome this problem, stress-inducible plant promoters with a low background expression level have been used in conjunction with the cold tolerance genes (Yamaguchi-Shinozaki and Shinozaki 1994).

ArborGen has introduced the *Arabidopsis* CBF2 transcription factor driven by the *Arabidopsis* rd29a stress-inducible promoter (Yamaguchi-Shinozaki et al.

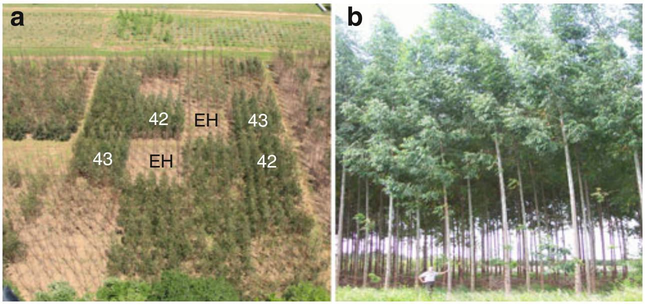

Fig. 7.5 ArborGen's Freeze Tolerant Eucalyptus field trials. **a** Aerial photograph of Freeze Tolerant Eucalyptus field trial planted in Alabama in a block plot design at age 2. EH Nontransgenic control trees; blocks 42, 43 two different transgenic lines of ArborGen Freeze Tolerant Eucalyptus containing the Arabidopsis CBF2 transcription factor driven by the Arabidopsis rd29a promoter. **b** Photograph of ArborGen Freeze Tolerant Eucalyptus trees at 3 years of age in Florida

1993) into variety EH1, a highly productive tropical *Eucalyptus* hybrid (*E. grandis* x *E. urophylla*). The new transgenic variety, "Freeze Tolerant Eucalyptus", has demonstrated tolerance to approximately 16°F (–9°C) across multiple years and multiple field trial locations (Fig. 7.5), while essentially maintaining its exceptional productivity (Cunningham et al. 2010; ArborGen, unpublished data).

The yields achievable with Freeze Tolerant Eucalyptus are predicted to meet or exceed those that have been defined by the DOE and others for the long-term feasibility of renewable energy production [i.e., 8–10 dry short tons acre^{-1} year^{-1} (English et al. 2006)]. The application of total biomass-driven management systems could further increase yields and reduce delivered costs. An added benefit of Freeze Tolerant Eucalyptus is its ability to coppice when managed appropriately. Coppicing allows for subsequent crops without the added costs of establishment (site preparation, seedling and planting costs), which can provide a higher return to landowners. Coppice crops can show increases in productivity relative to the initial single-stem harvest (Sims et al. 2001), but coppice yields will decline eventually over time. Re-planting will then become economically attractive as new varieties become available.

The types of genetic improvements discussed above will be important in optimizing the potential for purpose-grown trees to provide sustainable and economical feedstock options for the production of cellulosic ethanol and other forms of bioenergy. Table 7.6 summarizes the theoretical acreage needed to meet the "advanced biofuels" target in the 2007 RFS in the Southeastern US based on current productivity assumptions for loblolly pine and Eucalyptus under pulpwood and high-density coppicing scenarios. It is projected that it would require 118 million green short tons biomass to produce the 36 billion gallons ethanol mandated under the RFS. Productivity improvements with fast-growing species like Eucalyptuscan reduce the amount of land required to meet this target substantially (by a factor of three relative to traditionally managed open pollinated loblolly pine).

Table 7.6 Approximate productivity and total planted acreage needed to meet the Renewable Fuel Standard[d] (RFS) in the southeastern US using purpose grown pine or Eucalyptus

	Pinus taeda	*Eucalyptus urograndis*	
		Pulpwood management	Total biomass management
Productivity(green tons acre^{-1} year^{-1})	10[a]	20[b]	30[c]
Planted acres (million) needed to meet target 118 million green tons year^{-1}[e]	12	6	4

[a] ArborGen, unpublished data, assumes a 10-year rotation with a planting density of 1,000 trees per acre

[b] ArborGen, unpublished data, assumes a 7-year rotation, with 450 trees per acre

[c] ArborGen unpublished data, assumes an average product of an initial harvest at 3 years, followed by three coppice rotations of approximately 3 years coppice rotation, using a similar coppicing regime as described in Sims et al. 2001)

[d] On 19 December 2007, the Energy Independence and Security Act of 2007 (H.R. 6) was signed into law. This comprehensive energy legislation amends the RFS signed into law in 2005, growing to 36 billion gallons biofuels available in 2022

[e] Assumes 21 billion gallon ‘advanced biofuels’ target in RFS, Southeastern share of 28%, 100 gallons ethanol produced per dry ton biomass and a 50% moisture content (wet basis)

7.4.2 Genetic Improvement for Wood Properties

Once the trees planted for woody biomass achieve productivity levels that enable economically sustainable delivered feedstock costs, improvements in the wood itself can provide additional efficiency and cost improvements in biofuel or biopower conversion. There are two general technical targets for modifying the wood to increase the yield of ethanol per ton of wood via biochemical/biological processes, thereby reducing the “recalcitrance” of wood in bioconversion to ethanol. The first target is to modify the accessibility and/or degradability of cell wall polysaccharides to the enzymes and/or microorganisms used to break them down. The second target is to reduce the concentrations of fermentation inhibitory compounds that reduce the efficiency of ethanol production from released sugars.

The DOE has funded several bioenergy science centers to address biological and technological barriers in the cost effective production of biofuels from lignocellusic feedstocks. One such center, the BioEnergy Science Center managed by Oak Ridge National Laboratory, has focused research on reducing factors contributing to the recalcitrance of wood in biofuels conversion (US DOE Office of Science 2009) In addition, quantitative trait analysis of natural variation coupled with phenotypic screens for recalcitrance traits such sugar release efficiency, acid digestibility and general cell wall composition are underway as part of the BioEnergy Science Center.

One approach that addresses both technical targets discussed above is reduction of lignin in plant cell walls, or potentially the modification of the chemical composition of lignin, making it easier to remove. Reduction of lignin has long been a target of interest in crop and forestry species, because lignin content negatively affects the feed efficiency of forage for farm animals and lignin removal is one of the more costly steps in the kraft pulping process used in the paper industry. Extensive research has been conducted to understand the lignin biosynthetic pathway and enable the transgenic manipulation of lignin quantity and composition over the past 15 years (as reviewed in Anterola and Lewis 2002; Boerjan et al. 2003; Li et al. 2008; Vanholme et al. 2008; Weng et al. 2008). In general, it has been shown that lignin content can be significantly reduced in trees and herbaceous plants and that this can improve the ability to remove lignin and access cellulose for bioconversion processes (Hu et al. 1999; Lapierre et al. 1999; Chen and Dixon 2007; Li et al. 2008). For example, several of the transgenic plants with down-regulated genes for lignin biosynthetic enzymes in the early steps of the pathway showed that syringyl lignin (S-lignin) content was affected more strongly than the guaiacyl lignin (G-lignin) content (Vanholme et al. 2008).

Lignin reduction is often associated with negative pleiotropic effects. Examples of pleiotropic effects from lignin reduction in Populus include the accumulation of sugars in leaves and concomitant reduction of photosynthetic capacity following down-regulation of p-coumaroyl shikimate 3δ-hydroxylase (Coleman et al. 2008), or the reduction of hemicellulose associated with the down-regulation of cinnamoyl-coenzyme A reductase (Leplé et al. 2007). Increased cavitation and vessel collapse have also been observed in some plants with reduced lignin (Coleman et al. 2008). Achievement of economically valuable levels of lignin reduction will require the use of carefully selected promoters and target genes. Using transcription factors involved in controlling elements of the lignin biosynthetic pathway as the target genes may minimize the impact of negative pleiotropic effects since these genes control a group of genes in the lignin biosynthesis pathway. For example, two plant-specific transcription factors, designated NAC secondary wall thickenings promoting factor 1 (NST1) and 3 (NST3), regulate the formation of secondary walls in woody tissues of *Arabidopsis* (Mitsuda et al. 2007).

An increased syringyl lignin to guaiacyl lignin (S/G) ratio is thought to be desirable, because the more oxygen-rich S-lignin is easier to remove through chemical treatment (Chiang and Funaoka 1990). This can be achieved by over-expression of ferulate 5-hydroxylase (F5H), also known as coniferaldehyde 5-hydroxylase (Cald5H; Huntley et al. 2003). Interestingly, it has been reported that the composition of lignin does not have a strong effect on biological degradation of cell walls (Grabber et al. 1997), but that lignin levels have a highly significant impact on cell wall recalcitrance to saccharification (Chen and Dixon 2007; Li et al. 2008).

The polysaccharides themselves contribute a large part to recalcitrance because of their insolubility. In conifer and hardwood (angiosperm) secondary cell walls, cellulose is approximately 45% of the dry weight of the wood while hemicellulose is approximately 20% (Table 7.4). Hemicellulose composition varies strongly depending upon the wood source. The hemicellulose of hardwoods such as Populus is comprised of about 80% xylans, with the remainder being mannans (10%), galactans (5%) and arabinans (<5%). In pine, mannans comprise about 50%, xylans 30%, galactans 10%, and arabinans 5% of the total hemicellulose (Rowell 2005).

The DOE has funded three collaborative centers for research focused on improving lignocellulosic feedstock and related downstream processes for improved conversion efficiency. It is anticipated that within the next 5 years, from the overall US government investment in these research centers, much more will be known about genes that can be used to address the recalcitrance of plant cell walls to enzymatic biofuels conversion methods.

If wood is to be used simply as a fuel via burning, the two obvious targets for modification are increasing density and increasing lignin content. Increasing wood density has the potential of increasing the yield of fuel per acre and decreasing transportation and storage costs (increasing the energy yield per truckload of wood or chips), although the amount of energy per unit weight of wood would remain the same. Increases in wood density would improve the energy yield of wood produced via gasification. It seems unlikely that it would be possible to insert significantly more material into the cell wall matrix, but decreasing the ratio of lumen volume to cell wall volume is one avenue to increase wood density. As yet there is not much research demonstrating biotech approaches to improve wood density, although it has been shown that over-expression of a *Eucalyptus gunnii* MYB transcription factor (EgMYB2) in tobacco led to significant thickening of xylem fiber cell walls (Goicoechea et al. 2005). It was theorized that the thickened cell wall phenotype is due to an overall rate increase in deposition of the S2 layer of the secondary cell wall.

Increasing lignin content would increase the thermal energy of wood. Pure cellulose has a calorific value of approximately 8,000 BTU per pound of dry biomass (BTU/lb), while pure lignin is approximately 11,000 BTU/lb (White 1987), so an increase of 10% in lignin content would increase the calorific value of wood by approximately 450 BTU/lb. Lignin up-regulation could potentially be achieved by over-expression of an enzyme that is a kinetic barrier in the lignin biosynthetic pathway or via over-expression of a transcription factor that controls multiple lignin biosynthetic genes. Increased lignin deposition has been observed with the over-expression of certain MYB transcription factors (Patzlaff et al. 2003; Goicoechea et al. 2005).

7.5 Sustainable Production of Purpose-Grown Trees

Sustainability of natural resources involves economic, environmental, and social considerations. There are environmental impacts arising from the production of biomass, as there are in managing many natural resources. Sustainable production takes into account conservation of biological diversity, maintaining production capacity and forest ecosystem health, enabling soil- and water resource-conservation, attaining a positive impact on global carbon cycles, and allowing associated long-term socio-economic benefits.

Sustainable production is an important practice in forestry, and core principles involve managing working forests as landscapes for the preservation of biodiversity and watersheds, while allowing a diversity of uses and benefits for current and future generations (Reynolds et al. 2003; Reynolds 2005). Sustainable production of wood grown for industrial applications has been a priority of the forestry industry, and it is expected that sustainable practices will continue to be applied for wood production for biopower and biofuels applications (Raison 2002). Appropriate silvicultural practices can ensure sustainable wood production. Science-based studies of site productivity and harvesting have allowed the development of operational forest management guidelines that adjust harvesting operations to the biological and physical requirements of the site.

Land management has intensified over the last 20 years, particularly in Southeastern and Pacific-Northwest regions of the US, in tree plantations grown for pulp and lumber end-uses. Sustainably high yields have been demonstrated on tree plantations (or farms) over cycles of planting improved tree stocks and through management for enhanced growth that involves tillage, fertilization, irrigation, herbicide use, clear-cutting, and replanting (US Department of Agriculture 2002).

There is concern that repeated rotations of tree plantation silviculture may degrade site fertility and thus not be sustainable. This has not been demonstrated to be the case. In pine plantations in the Southeastern US, 50 lbs phosphorous per acre at establishment may have a positive impact on biomass yield for 20 years or more, and this fertilization can improve growth by over 100% on deficient sites. In addition, at canopy closure an additional fertilization of nitrogen and phosphorous can be applied, which results in an average growth improvement of 30% (Fox et al. 2006). A study on two loblolly pine plantations evaluated nitrogen (N) and phosphorous (P) pools before harvest, and compared the value of these two nutrients after ten growing seasons of the second rotation following plantation re-establishment. Second rotation soil N pools ranged from 3,134 to 5,148 kg/ha, and soil P pools ranged from 578 to 767 kg/ha, and these were equal to or significantly greater than those found at the end of the first rotation. Both plantations accumulated N and P faster than predicted by their age, which indicates that the management practices even conserved and allowed for the accumulation of nutrients. Maintenance of soil nutrient levels can be considered a strong indicator of sustainable production (Gresham 2002).

Intensively managed tree farms have a high potential for storing carbon (US Department of Agriculture 2008). Irrigated Pacific Northwest poplar plantations produce 49 tons of trunk and branch wood and 2 tons leaves per acre by the 4th year of production. This level of productivity increases the total amount of carbon that can be captured. This capture is manifested in the short term as paper and wood products, and in the long term as soil carbon from roots, exudates, and decomposed litter. Evidence of improved carbon content in tree plantations relative to annual crop plantings was described by Mann and Tolbert (2000). After the initial 4- to 6-year establishment period for a hybrid poplar plantation, the measured amount of organic carbon stored in the soil was 191 Mg/ha, and this was greater than that for row crops or grass. The increased carbon storage was especially noticeable at soil depths below 30 cm, where most of the coarse root development occurred (Mann and Tolbert 2000).

Biomass crop systems that increase organic carbon generally yield positive changes in soil structure, water-holding capacity, and the storage and availability of nutrients, and this facilitates increased abundance and diversity of soil biota as well as increased resistance to compaction. The amount of equipment traffic on the land and the amount of soil disturbance is much less in tree plantations than in land with annually planted crops. This is due to multiyear harvest cycle possible with trees. A comparison of cottonwood planting to cotton in the Southeastern US revealed that the cottonwood plantation had better soil structure than the cotton field (decreased density and increase in water stable soil aggregates), which correlated with a five-fold reduction of surface sediment runoff over a 2-year period of time (Mann and Tolbert 2000). Minimum tillage, such as occurs in short rotation woody crops after establishment, in particular can increase the organic carbon content in soils. Erosion losses in SRWC range from 2 to 4 metric tons ha^{-1} $year^{-1}$ as compared to the 14–41 metric tons ha^{-1} $year^{-1}$ losses associated with annual row crops in the southeast (Mann and Tolbert 2000).

Biodiversity conservation is a central subject in forest management and associated public policy. In managing planted forests there is emphasis on retaining patches of natural vegetation or riparian or wildlife corridors, and in some cases re-establishing native vegetation as part of overall plantation development. Trees compare favorably when compared to annually harvested bioenergy crops with respect to biodiversity and wildlife since tree plantations will remain largely undisturbed for several years. SRWC such as willow that are harvested on a 3-year rotation have provided a variation in habitat for wildlife since approximately one-third of the land that is just starting to grow a new stand is a open habitat while more mature stands are more of a shrub habitat. Therefore, SRWC would provide a structurally diverse environment across their managed landscape that would support a wider range of biodiversity than an annually harvested energy crop (Volk et al. 2004). Careful forest management in natural and/or planted forests can contribute to the conservation of biodiversity and to water regulation, carbon sequestration and recreational benefits. Short rotation tree plantations have much higher productivity than unmanaged forests and it is expected that concerns over the compatibility of bioenergy and biodiversity can be met by keeping biodiversity as a key element in managing woody biomass for bioenergy as a component of the overall forest landscape.

Woody biomass as bioenergy feedstock offers overall energy balance improvements, reduced greenhouse gas emissions, and reversal of deforestation via afforestation. Well-managed short rotation forests are a sustainable and renewable resource that is CO_2 neutral. Typical energy balances for forestry and agriculture systems indicate that 25–50 units of bioenergy are produced for every unit of fossil energy consumed in production (IEA BioEnergy 2002). Woody biomass grown for bioenergy systems could enhance carbon sequestration since short rotation trees produce vegetation and roots that are strong carbon sinks, with carbon being sequestered over a tree's multi-year rotation and through the persistence of roots in the soil after harvest (IEA BioEnergy 2002; Satori et al. 2006). Another potential benefit to short rotation tree plantations is that they can be used not just for wood production but also for bioremediation. SRWC can be used in conjunction with sewage waste disposal (Smart et al. 2005) and for soil amelioration (Rockwood et al. 2004). Economic sustainability is also enabled, since tree bioenergy plantations can be planted on unused or non-productive agricultural lands, creating additional jobs in rural economies. Given supportive policies, woody biomass will provide a sustainable solution to future bioenergy demands.

Genetically improved trees through the insertion of biotech traits will contribute significantly to the US reaching its objectives of sustainable production of biopower and biofuels. Since the commercialization of the first biotech crops in 1996, the adoption rate of biotech crops has increased rapidly worldwide, with over 2 billion acres planted in 25 different countries (ISAAA 2008). Field tests of genetically modified trees are being conducted in several countries, with the majority of these field tests occurring in the US (van Frankenhuyzen and Beardmore 2004). To date, only two tree species, papaya and plum, have been granted non-regulated status for planting in the US. These fruit trees were made resistant to viruses that can have devastating impacts on fruit production and quality. Currently the only large-scale plantings of transgenic forest trees are insect-resistant poplars that are being grown in China (Hu et al. 2001). More recently, a petition was submitted to USDA APHIS Biotechnology Regulatory Services (BRS) requesting non-regulated status for the Freeze Tolerant *Eucalyptus* hybrid described in Sect. 7.5.1.3.

While it is recognized that the use of biotechnology for tree improvement can bring significant economic, social and environmental benefits, some concerns have been expressed (van Frankenhuyzen and Beardmore 2004), particularly associated with the potential dispersal of pollen, seeds, or vegetative propagules. Gene flow via pollen and seed dispersal is an important natural phenomenon for genetic improvement and evolution in plant species. The potential for gene flow from crops, be it from traditional breeding or developed through biotechnology, is considered to be less for non-native self-pollinated crops compared to native and wind pollinated species. Perennial wind pollinated species models predict that a small proportion of pollen and seed can travel considerable distances (Nathan et al. 2002; Williams 2005; Williams and Davis 2005; see Chaps. 9–11, this volume). However, for there to be any consequences of such dispersal, these models assume that the following: (1) viable pollen is able to fertilize receptive ovules of a related species resulting in viable seed production, followed by establishment of this seed in the environment; and (2) adverse consequences can occur only if the inserted genes are considered a significant risk to other organisms or can cause unintended effects on the fitness of the species. Traits including improved growth, wood quality and abiotic or biotic stress tolerance that are also being altered via traditional breeding might be considered as being inherently low risk, particularly when using genes from the tree itself, or other plant genes that are homologous to genes already present in the tree, and where no unintended phenotypes have been observed after extensive field testing. In some cases, especially for biomass production for bioenergy uses, short rotation trees may not even produce significant amounts of pollen or seed prior to harvest. In addition, there are proven and well tested technologies that selectively prevent or reduce pollen formation without affecting other functions of the plant species (Nasrallah et al. 1999; Gomez Jimenez et al. 2006; Yanofsky 2006; Chap. 10). ArborGen has adapted this technology for use in tree species and has demonstrated high levels of efficacy (Hinchee et al. 2009). Therefore, a number of tools exist that can minimize the potential risk of gene flow via pollen or seed dispersal from plantations. It is important however, that any risk assessments for trees take into account scientifically informed arguments for incorporating any such gene flow control mechanisms on a case-by-case basis.

7.6 Conclusion

The existing wood products industries have led the development of sustainable production, management, harvest, and transportation systems for the production of hundreds of millions of tons of wood from planted trees in the US annually. Existing infrastructure and know-how in intensively managed tree plantations for purpose-grown trees already exists, and this resource can be built upon to meet renewable energy goals and help mitigate climate change.

The high productivity of purpose-grown, short rotation trees is expected to improve the economic feasibility of biopower and biofuels production from woody biomass plantations. Woody biomass represents about two-thirds of the near-term potential of the Southeastern US for producing renewable energy, and bioenergy is already becoming a substantial market outlet for wood. Sixteen bioenergy projects have been announced throughout the Southeast that would consume nearly 50 million green short tons woody biomass by 2015. The development of a bioenergy sector in the Southeastern US holds great economic promise, and it is anticipated that purpose-grown, short rotation trees will be planted to address the 120 million green short tons of biomass that will be needed annually as a feedstock for advanced biofuels. At an estimated price of US $20 to US $30 per green short ton, this represents US $2–4 billion in economic opportunity associated with biomass production for the Southeastern US. Upside demand exists because of the suitability of wood for other bioenergy applications, such as the production of electricity through direct burning of wood or co-firing with coal.

To achieve lower production costs, the supply of cheap raw materials is thus a necessity. Accordingly, it will be possible to produce large amounts of low-cost ethanol only if lignocellulosic feedstock, such as fast-growing trees and grasses, are used along with waste products (including agricultural and forestry residues) and municipal and industrial wastes (Wheals et al. 1999). The inherent logistical benefits of trees, in combination with the high productivity of new varieties of short rotation trees such as Freeze Tolerant Eucalyptus, make it an ideal biomass for traditional industrial end uses such as pulp and paper, as well as for energy products such as cellulosic ethanol and electric power generation. Short rotation trees will generate more wood on less land, requiring a smaller plantation footprint to generate the necessary dry tons to feed industrial processing plants. This, in turn, will lessen pressure to harvest from native and old growth forests in order to meet society's demand for pulp, paper and energy. The addition biotech traits to elite varieties of purpose-grown trees will help achieve the short rotation times, high productivity, and target delivered costs of wood to make lignocellulosic feedstocks cost effective.

The choice of energy crops to plant must take into consideration regional conditions and needs, both in minimizing transportation costs as well as avoiding the current long distance distribution limitations of ethanol. In the Southeastern US, where accessible inventory and harvesting infrastructure for forestry operations are already well established, trees provide a clear advantage for biomass production compared to annual crops. Trees will play a significant role in helping to meet renewable energy standards, although it is recognized that multiple integrated approaches with a variety of different crop species and production systems will be required to meet our total renewable energy objectives.

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